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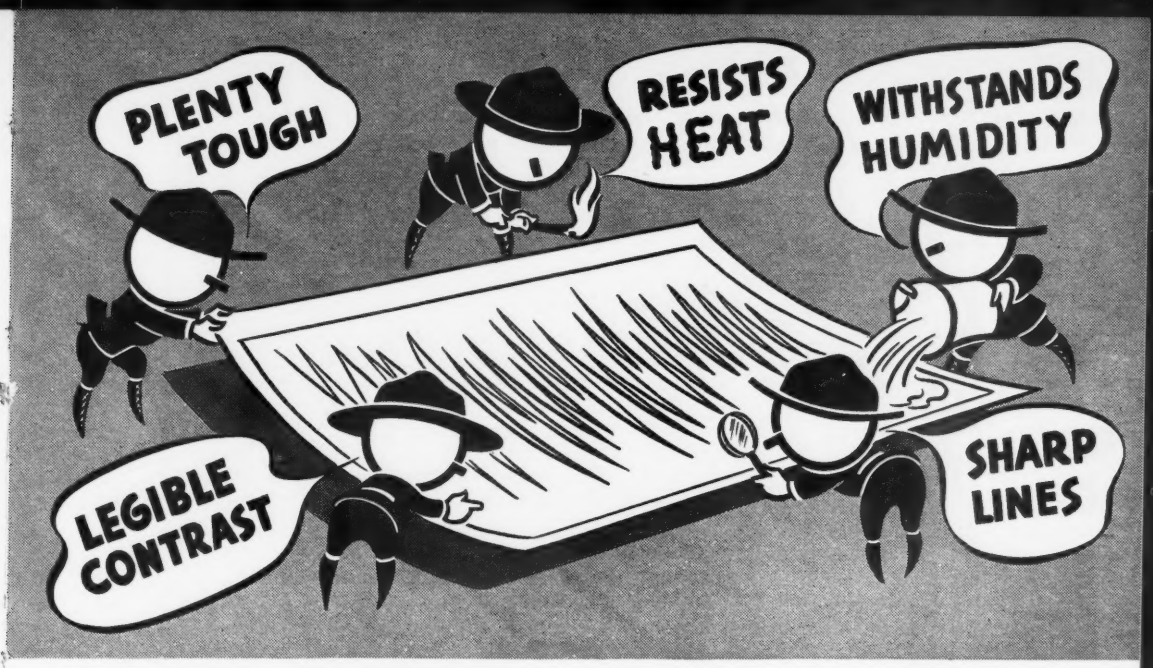

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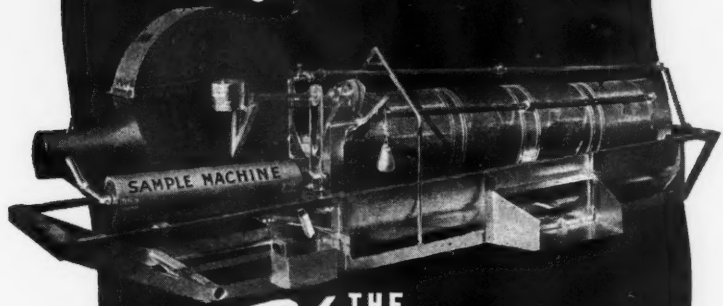

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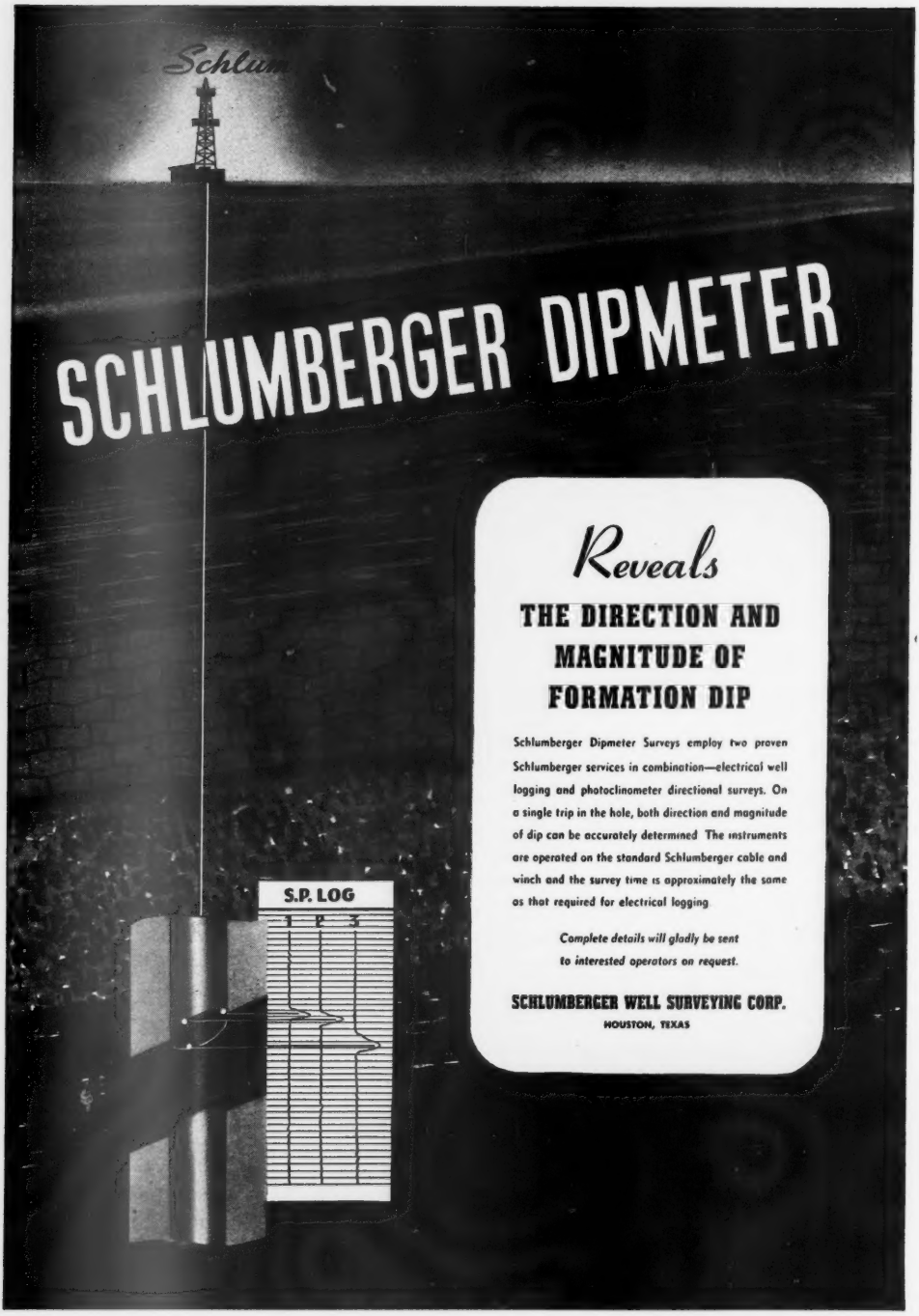
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Stratigraphy and Age of Seguin Formation of Central Texas
By M. W. Beckman and F. E. Turner

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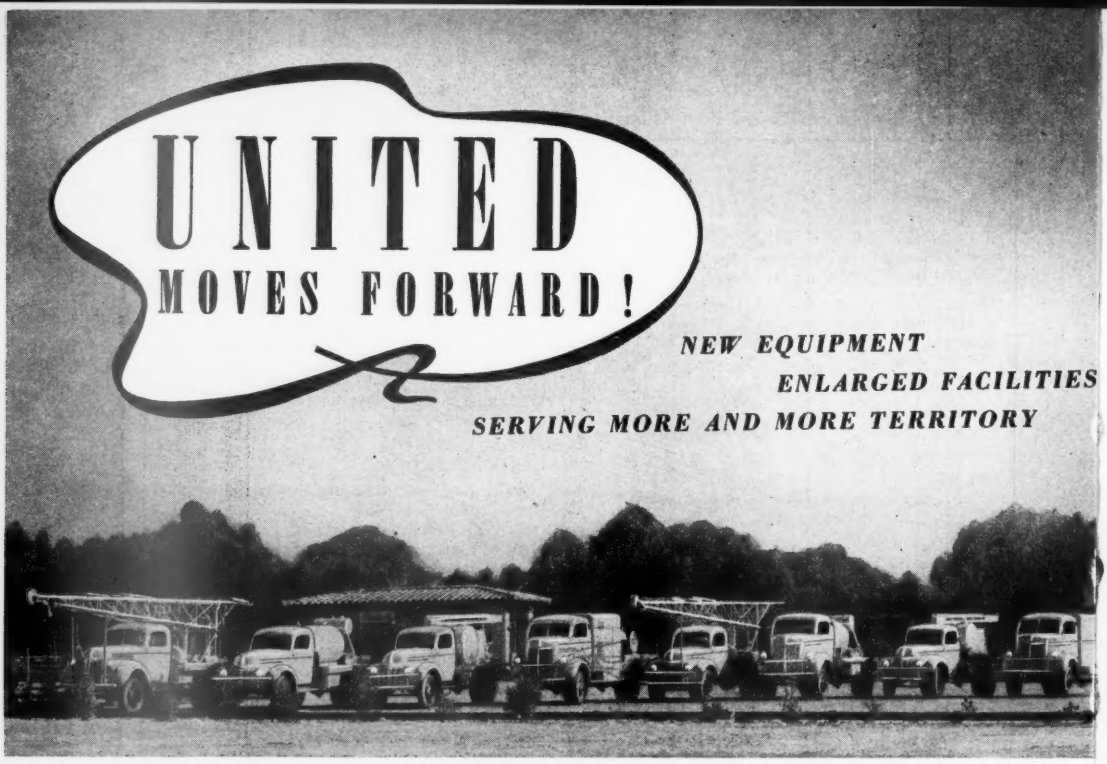

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APRIL, 1943

STRUCTURAL CONDITIONS OF OIL AND GAS ACCUMULATION IN ROCKY MOUNTAIN REGION, UNITED STATES[1]

C. E. DOBBIN[2]
Denver, Colorado

ABSTRACT

This paper is a summary account of the structural conditions under which oil and gas have accumulated in the Rocky Mountain region, supplemented with data on the diastrophic history and tectonic pattern, the origin of the producing structures, the age and character of the productive zones, and copious citations of relevant literature. Maps, charts, and tables are substituted for lengthy discussions of many topics.

A graph shows that since 1927 there has been a marked decline in the number of oil and gas fields discovered in the region. Regional maps show the main structural elements and the locations of the oil and gas fields in the physiographic provinces. State maps show the geographic relations of the oil and gas fields to the main structural elements. Maps of typical producing structures are included, and a chart shows columnar sections in representative oil and gas fields. Tables give many geologic details on all fields.

Oils of highly divergent character have been produced from strata ranging in age from lower Mississippian to Oligocene, and strong showings of oil have been found in several pre-Mississippian series. The oldest oils tend to be heavy and the youngest oils light. Some of the natural gases are rich in helium and carbon dioxide. The productive zones are highly variable in character, and the quality of the oil bears no demonstrable relation to the dynamic metamorphism that the region has undergone. The carbon-ratio theory can not be indiscriminately applied to the Rocky Mountain region, where most of the Cretaceous and early Tertiary coals are low in rank.

INTRODUCTION

Although the Rocky Mountain region—which herein includes the Rocky Mountain system, the Colorado Plateaus, and the western part of the Great Plains north of central New Mexico—has produced only a relatively small amount of oil since the first oil well therein was completed near Canon City, Colorado, in 1862, it is of special interest to petroleum gelogists for these reasons: oils of highly divergent character have been produced from strata ranging in age from lower Mississippian to Oligocene and strong showings of oil have been reported locally from several pre-Mississippian series; the oldest oils tend to be heavy and the youngest oils light; oil and gas occur in almost all known types of traps—

[1] Manuscript received, June 15, 1942. Published by permission of the director of the Geological Survey.

[2] Geological Survey, United States Department of the Interior.

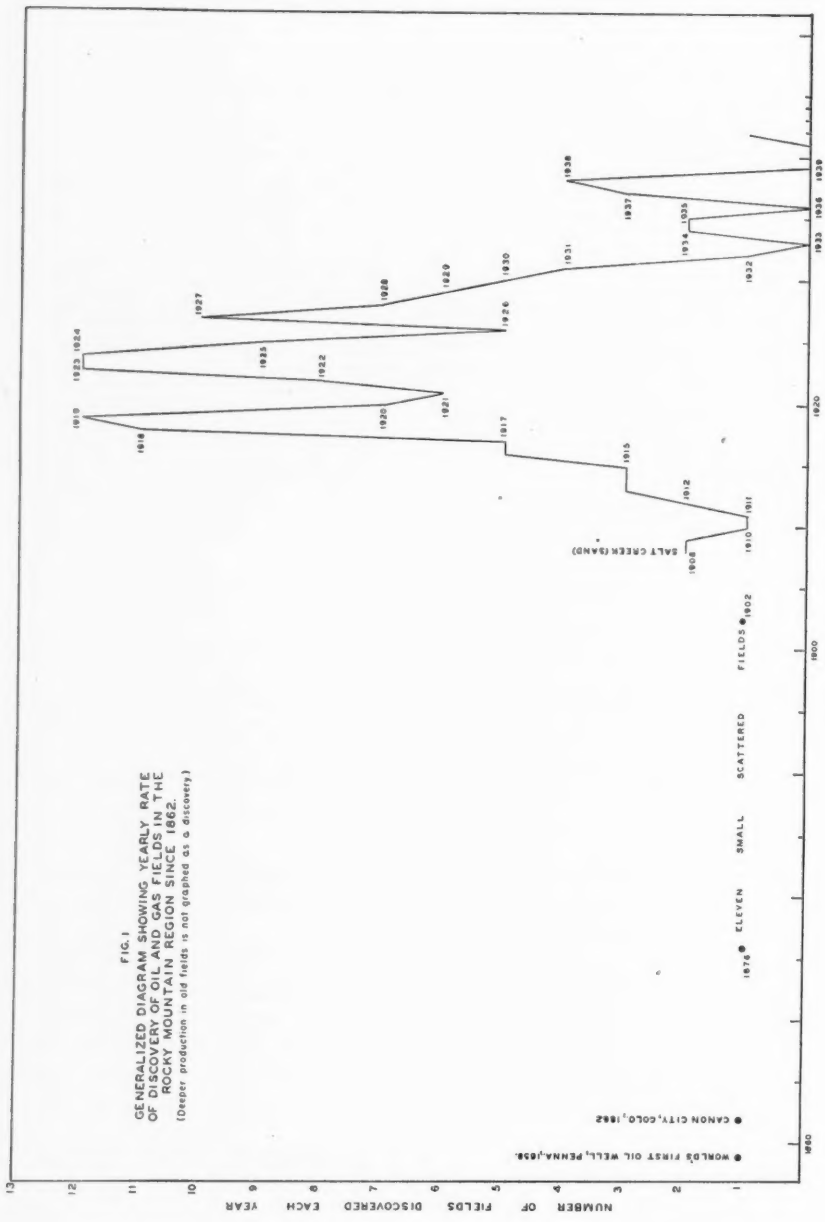


FIG. 1
GENERALIZED DIAGRAM SHOWING YEARLY RATE OF DISCOVERY OF OIL AND GAS FIELDS IN THE ROCKY MOUNTAIN REGION SINCE 1862.
(Deeper production in old fields is not graphed as a discovery)

even some in salt domes—and beds in several different series yield oil and gas in one field; some of the natural gases are rich in helium and carbon dioxide; the producing zones are exposed in mountainous uplifts rather close to the producing fields; and, on a tectonic basis, the region contains—along with contiguous parts of Canada—the most extensive group of oil fields known.

A close study of available data indicates that the transformational history of oil and gas in the region has been complex and that missing factors in that history may be largely responsible for the many conditions of accumulation that defy reasonable explanation and prevent researchers from concocting generally acceptable theories as to the origins of the oil and gas and the means of their arrival at present traps.

This factual and statistical paper outlines some of the broader geologic events and conditions related to and partly responsible for oil and gas accumulation in the region and tabulates many relevant details in proved areas. Maps, charts, and tables are substituted for lengthy discussions of certain topics—for instance, stratigraphy. The nomenclature as given on the charts accords with that in current use among oil geologists in the Rocky Mountain region.

Acknowledgments

Almost all the geologic literature on the Rocky Mountain region was consulted in the preparation of this paper, and acknowledgments are herewith made to its authors. The Geologic Map of the United States and the geologic maps of Arizona, Colorado, New Mexico, and Wyoming, by the Federal Geological Survey, are sources of many of the data shown in Figures 3, 4, 5, 9, and 11. The charts showing correlations of the named geologic units of the various Rocky Mountain states, prepared by Miss Grace Wilmarth, formerly secretary of the Committee on Geologic Names, Geological Survey, and her "Lexicon of Geologic Names of the United States" (*Bull. 896*) were used in preparing Figure 14 and the tables showing surface types of oil and gas fields.

Many data shown in the tables were drawn from the records of petroleum engineers in the Geological Survey, who have supervised oil and gas operations on the public domain for the Survey since 1925. J. C. Miller, of the Geological Survey, read the text critically and offered constructive suggestions.

The illustrations were prepared by Misses Lillian Cummings and Dolly Furness of the Geological Survey.

Herman Stabler and J. D. Northrop, chief and assistant chief, respectively, of the Conservation Branch of the Geological Survey, provided many of the means for carrying out the study.

Brief History of Oil and Gas Development

Largely because of a lack of markets and good transportation facilities, drilling for oil and gas in the Rocky Mountain region was carried out desultorily during the period 1862–1911 (Fig. 1), oil having been found at 21 localities and gas at

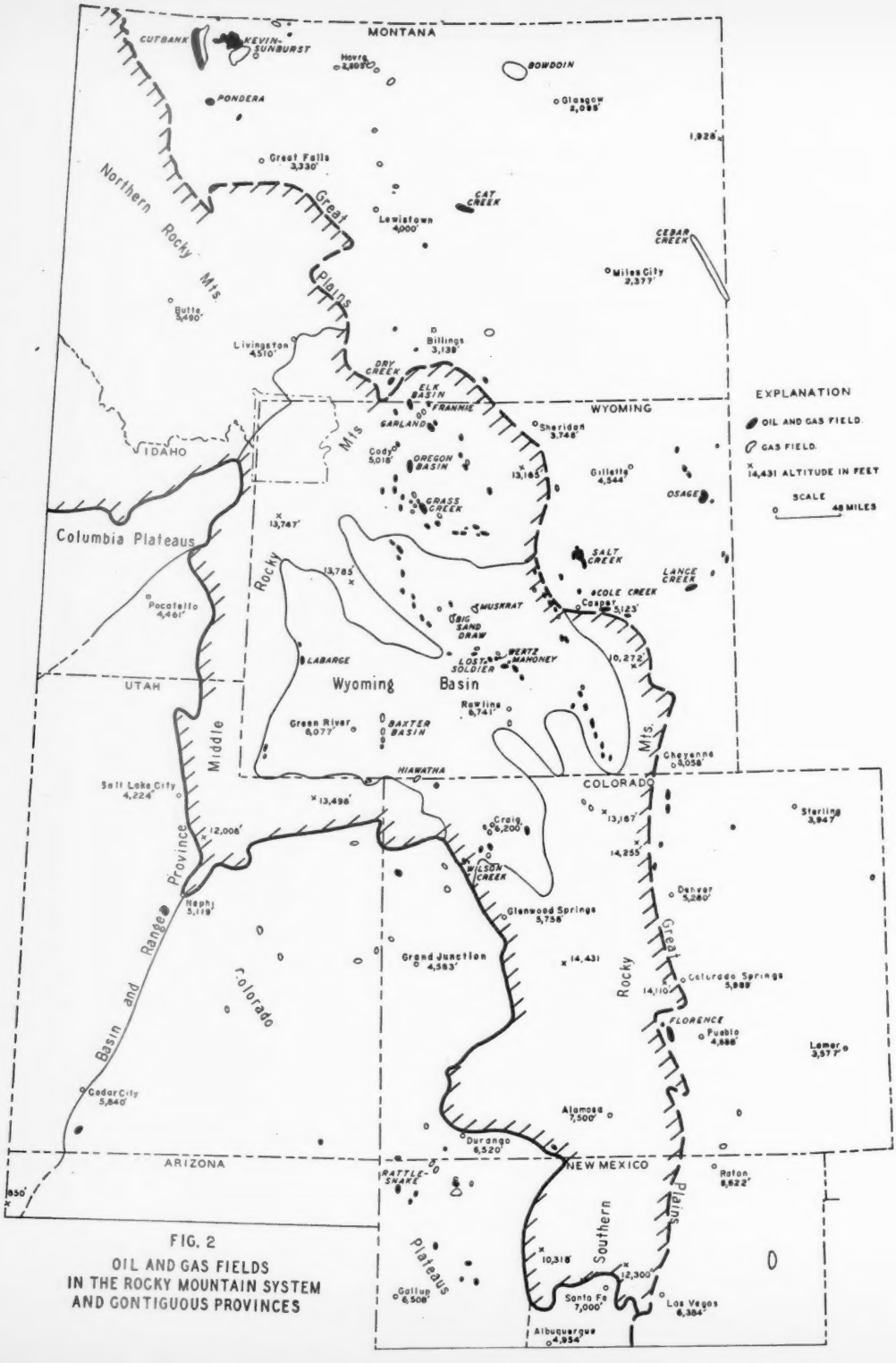


FIG. 2
OIL AND GAS FIELDS
IN THE ROCKY MOUNTAIN SYSTEM
AND CONTIGUOUS PROVINCES

two localities. Nine of these early oil fields were situated near oil springs on monoclines—none ever becoming relatively important—and at least six more were located near oil springs or gas seepages on well defined anticlines, only two—Garland and Salt Creek—becoming relatively important producers of oil later.

Diligent search for oil and gas in the region on the basis of the anticlinal theory apparently began during the period 1912–1915. The years 1919, 1923, and 1924 saw the largest number of fields discovered in any one year, and since 1927 there has been a marked decline in the number of fields discovered.

Physiographic Outline

Oil or gas—or both—have been produced at about 180 localities in the Rocky Mountain region, 32 per cent lying in the Great Plains, 52 per cent in the Rocky Mountain system, and 16 per cent in the Colorado Plateaus (Fig. 2).[3] All the Montana oil and gas fields lie in the Great Plains; 80 per cent of the Wyoming fields lie in the Rocky Mountain system and 20 per cent in the Great Plains; the Colorado fields are about equally distributed between the Great Plains, the Rocky Mountains, and the Colorado Plateaus; and almost all the fields in northern New Mexico and in Utah lie in the Colorado Plateaus.

The lowest surface elevation in a producing field is about 2,167 feet in the Bowdoin gas field, Montana, and the highest is about 8,000 feet in the Wilson Creek, McCallum, and Price fields, Colorado. The highest altitude in the area covered by Figures 2 and 3 is 14,431 feet atop Mt. Elbert, Colorado, and the lowest is about 850 feet on Colorado River in northwest Arizona.

Diastrophic History

The deposition, during the late pre-Cambrian, of a very thick series of shale and limestone in western Montana and vicinity and of thick, chiefly sandy beds in northeastern Utah, southwestern Colorado, and the Grand Canyon area foreshadowed, that early, the extensive geosyncline that was present in and west of the present Rocky Mountain region until near the end of Upper Cretaceous time and played a very important part in the history of oil and gas there. Later pre-Cambrian orogeny in the four areas last named is the oldest one clearly differentiated in the Rocky Mountain region and vicinity.

Deposition during the Lower Cambrian in the Rocky Mountain region was probably restricted to a few relatively small areas along the western border of the region. However, during Middle and Upper Cambrian time progressive sinking caused the deposition of overlapping sandstone, shale, and limestone over most of the region, exclusive of southeastern Wyoming, much of northern and southern Colorado, northern New Mexico, northeastern Arizona, and central and southeastern Utah.

In Lower and Middle Ordovician time, the sea was not present over most of

[3] The boundaries of physiographic provinces shown on Fig. 2 are after Nevin M. Fenneman, *Physiography of Western United States*, McGraw-Hill Book Company, Inc. (1931).

the Rocky Mountain region, deposition there during those epochs being thickest in north-central Utah and progressively thicker southwest therefrom to southwestern Nevada and contiguous parts of California. However, a relatively thin limestone and a thin sandstone were deposited in a northwest-southeast-trending strait across central Colorado and contiguous areas during the Lower and Middle Ordovician, respectively.

Although expanding seas in the Upper Ordovician deposited relatively thin limestone beds over much of the Rocky Mountain region, Ordovician beds seemingly are not present in extreme western Montana, southeastern Wyoming and adjoining parts of Colorado, extreme southern Colorado, except in the southeastern part, northern New Mexico, northern Arizona, and most of southern Utah.

The Silurian system is represented in the Rocky Mountain region only by dolomite in southeastern Idaho and northern Utah, this period and the ensuing Lower Devonian being epochs of erosion over the remainder of the region.

Important subsidence in the Middle Devonian in parts of the Rocky Mountain region is proved by the presence of a relatively thick section of limestone and dolomite of that age in southeastern Idaho, northern Utah, and western Wyoming and of similar but thinner deposits in central and western Montana.

In the Upper Devonian, shale and limestone were deposited over all the areas last named, in most of southwestern Colorado, and locally in northern Arizona. However, most of Wyoming, eastern Utah(?), much of Colorado, and all northern New Mexico seemingly was land throughout the Devonian.

Regional subsidence in the Mississippian is shown by the actual and inferred deposition of the Madison limestone (lower Mississippian) and its equivalents over most of the Rocky Mountain region, and by the less widespread deposition of the lithologically variable Big Snowy group (upper Mississippian) of Montana, and its southern equivalents.

A probable early phase of Wichita orogeny in central Colorado during the upper Mississippian formed the north-south Colorado geanticline,[4] ancestral to the Front Range and Wet Mountains, in sympathy with the beginning of a world-wide orogenic cycle.[5] Broad warping was probably initiated in north-central Wyoming and in southern Montana at this time and also in the present Sweetgrass arch area, Montana, where later pre-Upper Jurassic erosion produced many of the conditions responsible for present oil and gas accumulation in the top of the Madison limestone. Whether the Madison was deposited in the present Front Range of Colorado and in northern New Mexico is debatable.

Pennsylvanian time was featured in parts of Colorado and in adjoining parts

[4] W. S. Burbank, "Relation of Paleozoic and Mesozoic Sedimentation to Cretaceous-Tertiary Igneous Activity and the Development of Tectonic Features in Colorado," *Amer. Inst. Min. Met. Eng.*, Lindgren Volume (1933), p. 279.

[5] W. A. J. M. van Waterschoot van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 9 (1931), pp. 991–1057.

of Wyoming, New Mexico, Arizona, and Utah by the progressive uplift and deformation of both combined and isolated positive areas contemporaneously with Arbuckle orogeny;[6] evaporite basins were present in southeastern Utah and in west-central and southwestern Colorado,[7] in western Nebraska[8] and southeastern Wyoming; and a broad land mass was present in northern Montana. Elsewhere in the Rocky Mountain region the sea was present, except in local areas of alluvial clastics bordering the aforementioned rising positive areas.

Toward the end of the Pennsylvanian, some of the uplifts in central Colorado, northwestern New Mexico, and eastern Utah, satellite to the so-called Ancestral Rockies, disappeared, the latter mountains probably having attained considerable elevation during late Pennsylvanian and Permian time.[9]

Permian time in the Rocky Mountain region saw transgressive marine sedimentation spreading east, south, and southwest to southwest Montana, western Wyoming, central Utah, central and southern New Mexico, and over most of Arizona, grading eastward into continental redbeds derived from landmasses in central and southwestern Colorado and vicinity and from broad landmasses in northern Montana. The redbeds in turn grade into marine limestone south and east in central New Mexico, western Kansas, and western Nebraska.

In southwestern Colorado, the formation of the San Juan upland by local orogeny in later Permian and Triassic time evidently constituted the last phase of Paleozoic mountain building in Colorado.[10]

By Lower Triassic time most of the Colorado land masses had been reduced to low altitudes. Except in much of northwestern Montana and eastern Colorado, most of the Rocky Mountain region throughout Triassic time received deposits of fluviatile redbeds though in the early Triassic slow oscillatory movements initiated marine invasion from the west, covering much of Utah, northwestern Arizona, and southeastern Idaho.

In Upper Triassic time, southern Idaho, central Nevada, and contiguous areas began to rise and blocked marine connections between the Rocky Mountain region and the Pacific Ocean. Coarse sediments were washed eastward in increasing amounts from this elevated area during Jurassic and Cretaceous time, thus re-

[6] The Wichita and Arbuckle orogenies are ably discussed in the aforecited paper by van Waterschoot van der Gracht.

Walter A. Ver Wiebe, "Ancestral Rocky Mountains," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 6 (1930), pp. 765–88.

[7] A. A. Baker, C. H. Dane, and John B. Reeside, Jr., "Paradox Formation of Eastern Utah and Western Colorado," *ibid.*, Vol. 17, No. 8 (1933), pp. 963–80.

Thomas S. Harrison, "Colorado-Utah Salt Domes," *ibid.*, Vol. 11, No. 2 (1927), pp. 111–33.

H. W. C. Prommel and H. E. Crum, "Salt Domes of Permian and Pennsylvanian Age in Southeastern Utah and Their Influence on Oil Accumulation," *ibid.*, Vol. 11, No. 4 (1927), pp. 373–93.

[8] John G. Bartram, "Summary of Rocky Mountain Geology," *ibid.*, Vol. 23, No. 8 (1939), p. 1141.

[9] Ross L. Heaton, "Ancestral Rockies and Mesozoic and Late Paleozoic Stratigraphy of Rocky Mountain Region," *ibid.*, Vol. 17, No. 2 (1933), p. 135.

[10] W. S. Burbank, *op. cit.*, p. 281.

versing the relation extant during much of Paleozoic and early Mesozoic time, when the site of the present Great Basin was dominantly a depressed area in which a vast thickness of sediments accumulated.

During early Jurassic time, the positive area described in the preceding paragraph rose higher and clastic sediments therefrom were deposited toward the east in the present Rocky Mountain region, eolian deposits being relatively thick in Utah, southwestern Colorado, northwestern New Mexico, northern Arizona, and southeastern Nevada. Subsequent crustal warping on a broad scale initiated marine deposition in early Upper Jurassic time from central Utah far into Canada and eastward into Wyoming and northwestern Colorado.[11]

The close of the Jurassic was featured by the widespread deposition of the continental Morrison formation. In the western and southwestern parts of the region some local orogeny in the late Upper Jurassic occurred contemporaneously with Nevadian diastrophism, and continued into the Upper Cretaceous.

Lower Cretaceous time in the Rocky Mountain region was featured by further spreading of sediments over flood plains. Broad crustal warpings, however, initiated a marine invasion at this time, chiefly in parts of eastern Colorado.

At the beginning of the Upper Cretaceous a great interior sea spread over the Rocky Mountain region and contiguous regions east of the aforementioned positive area in southern Idaho, central Nevada, and contiguous areas, the area of thickest sediments occurring in and near northeastern Utah.[12]

Premonitory phases of Laramide diastrophism began in the late Upper Cretaceous over most of the Rocky Mountain region. In parts of western Colorado an older cycle of volcanism, in which a climax of extrusive activity occurred in late Cretaceous and early Eocene preceded and accompanied the climax of deformation in the Front Range and the ancestral San Juan Mountains.[13]

It is believed that the climax of Laramide orogeny occurred in the early Eocene, after the deposition of the Fort Union formation and prior to the deposition of the Wasatch formation. However, one agrees with Spieker that

> the Great Basin and bordering areas to the east show the orogenic history of this region to comprise, instead of two or three concentrated "revolutions," a series of orogenic episodes, beginning in the Upper Triassic and extending to the late Tertiary.[14]

His observation that the effects of even the strongest orogenies were local cor-

[11] A. A. Baker, C. H. Dane, and J. B. Reeside, Jr., "Correlations of the Jurassic Formations in Parts of Utah, Arizona, New Mexico, and Colorado," *U. S. Geol. Survey Prof. Paper 183* (1936).
Ross L. Heaton, "Contribution to Jurassic Stratigraphy of Rocky Mountain Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 8 (1939), pp. 1153–77.
Joseph Neely, "Stratigraphy of the Sundance Formation and Related Jurassic Rocks in Wyoming and Their Petroleum Aspects," *ibid.*, Vol. 21, No. 6 (1937), pp. 715–70.

[12] H. F. Davies, "Structural History and Its Relation to the Accumulation of Oil and Gas in the Rocky Mountain District," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), p. 686.

[13] W. S. Burbank, *op. cit.*, p. 300.

[14] Edmund M. Spieker, "Orogenic History of Central North American Cordillera," *Bull. Geol. Soc. America*, Vol. 50, No. 12, Pt. 2 (1939), p. 1969.

responds with the evidence of Ball,[15] who states that some of the major uplifts were practically complete by the beginning of Wasatch time, while others were at that time still in the process of formation.

Bauer states that

> the Sweetwater anticline, including the Granite Mountains, was fully involved in the great folding and faulting at the close of Fort Union deposition, and again in a similar orogenic movement, after Wind River deposition.[16]

Love[17] postulates eight pulsations of Laramide orogeny in northwestern Wyoming, the first probably coming at the close of Lance time and the eighth after the deposition of 3,000 feet of Oligocene(?) pyroclastic rocks, the intrusion of plugs, extrusion of flows, and the climax of Cenozoic volcanism.

The Oligocene and lower Miocene were largely epochs of slow sedimentation in the central part of the Rocky Mountain region and eastward beyond the present Rockies. Normal faulting that began locally in the upper Eocene continued into late Tertiary time—and even to the present along the western border of the region. Explosive volcanism that followed the climax of folding and faulting also continued rather locally through the Pliocene and Pleistocene into the Recent.

The present structure in most of the Rocky Mountain region probably resulted from combinations of vertical stresses and subsequent tremendous compressive stresses exerted generally from the west during the various orogenic episodes of the late Cretaceous and early Tertiary Laramide "revolution."

Although Laramide orogeny accounts for most of the total observable deformation in the Rocky Mountain region, it is clear that some of the major Laramide uplifts, such as the Sangre de Cristo Mountains, the Front Range, and the Wet Mountains of Colorado, are rejuvenated Carboniferous uplifts. However, Laramide orogeny formed most of the structures in the region in which oil and gas have accumulated by gravity adjustment.

The present dissected Rocky Mountains are largely the result of several post-Laramide rejuvenative movements in the Tertiary and Quaternary, separated by periods of erosion, the high altitudes of some ranges being largely caused by renewed movements along faults and by regional arching.

Laramide Tectonic Pattern (Fig. 3)

Great Plains

Conspicuous uplifts in that part of the Great Plains herein considered include the elongate, dome-shaped Black Hills (present maximum elevation, 7,242 feet)

[15] Max W. Ball, "The Relative Ages of Major and Minor Folding and Oil Accumulation in Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 1 (1921), p. 53.

[16] C. Max Bauer, "Wind River Basin," *Bull. Geol. Soc. America*, Vol. 45, No. 4 (1934), p. 685.
Note: The Wind River formation is equivalent to the upper two faunal zones of the Wasatch formation.

[17] John David Love, "Geology along the Southern Margin of the Absaroka Range, Wyoming," *Geol. Soc. America Spec. Paper 20* (1939), pp. 116–17.

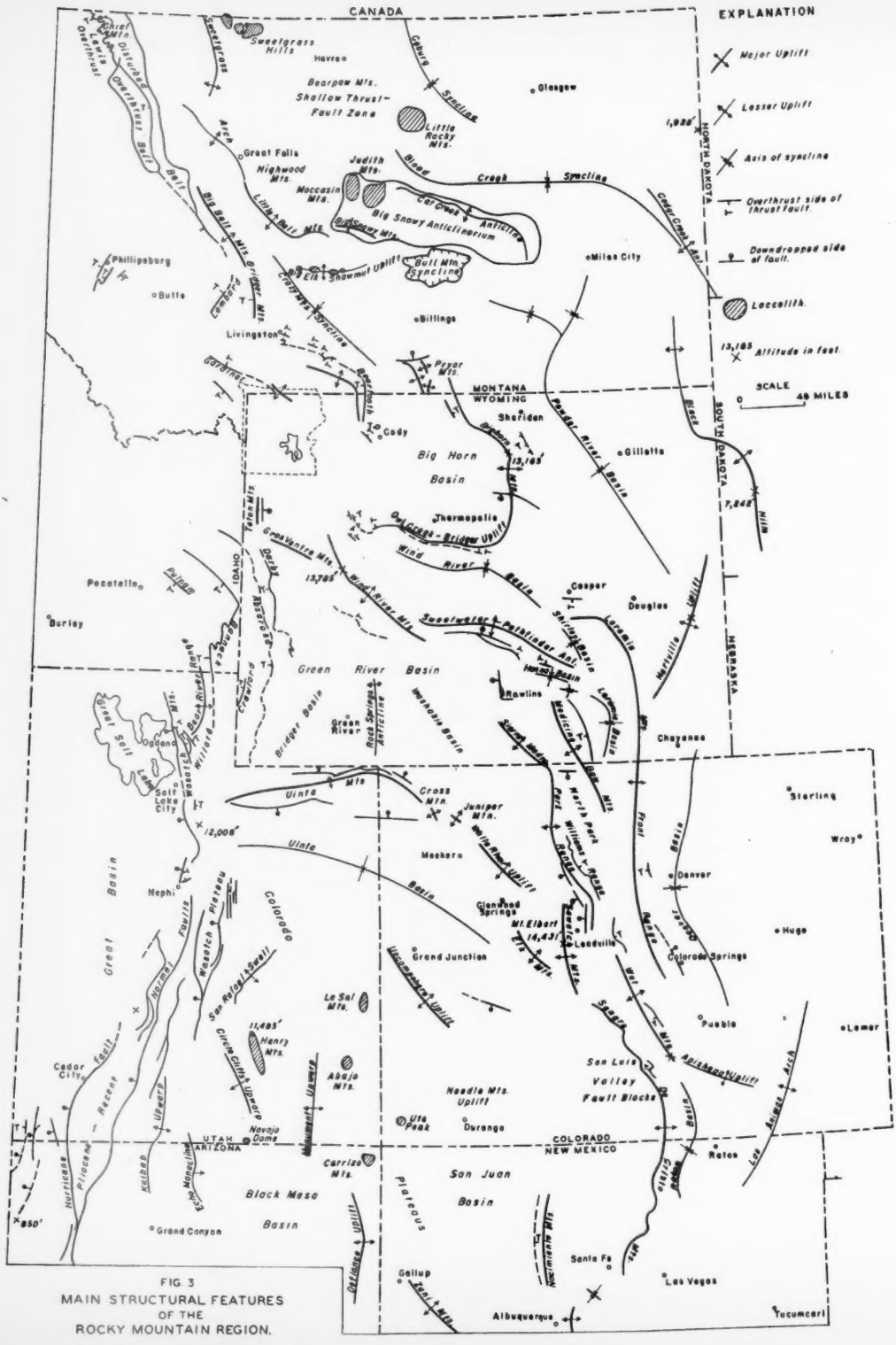


FIG. 3
MAIN STRUCTURAL FEATURES
OF THE
ROCKY MOUNTAIN REGION.

in northwestern South Dakota, and adjacent parts of Wyoming, and the following in Montana: the broad, horst-like tilted blocks, anticlines, and laccoliths comprising the Big Snowy anticlinorium (8,600± feet), and the laccolithic Little Rocky Mountains (6,600 feet) and Sweetgrass Hills (6,977 feet). Lower uplifts include the Las Animas arch in northeastern New Mexico and southeastern Colorado, the Hartville uplift in eastern Wyoming, the Big Elk-Shawmut laccolithic uplift near central Montana, and the Sweetgrass arch in northern Montana. Just west of the Sweetgrass arch and east of the major overthrust belt lies the "disturbed belt"—a relatively low area broken by many thrust faults that locally have displaced surface anticlines. The Highwood Mountains (7,600 feet) and the Bearpaw Mountains (7,000± feet) in north-central Montana are largely isolated masses of Tertiary extrusives with smaller areas of intrusives.

The principal structural basins in the Great Plains are the asymmetrical Raton basin in southeastern Colorado and vicinity, the asymmetrical Denver basin just east of the Front Range in Colorado, the Powder River basin in northeastern Wyoming and vicinity, and the Bull Mountain syncline in south-central Montana.

ROCKY MOUNTAINS

FRONTAL ZONE OF MAJOR THRUSTING

Extending from Chief Mountain, Montana, southeastward to Cody, Wyoming,[18] and thence interruptedly south-southwestward to and beyond the southwestern corner of Utah, the Rocky Mountains and parts of contiguous provinces are featured by a broad, arcuate zone of major asynchronous thrusting—the eastern edge of the inner zone of the Cordilleran system. In this zone at and south of Chief Mountain, strata of the pre-Cambrian Belt series have overridden Mesozoic beds along the frontal Lewis overthrust, the major overthrust zone facing directly on the disturbed belt of the Great Plains. South to Missouri River a number of almost parallel overlapping plates of Madison limestone (lower Mississippian) are thrust eastward at high angles over Cretaceous strata in a relatively broad overthrust belt. South of Missouri River, the thrust zone passes west of the Big Belt Mountains uplift and may join the Lombard thrust, which has also carried Belt strata over Cretaceous strata.

Between Livingston, Montana, and Cody, Wyoming, the frontal zone of major thrusting converges with the north extension of the elongate, individual linear uplifts, comprising the outer zone of folding in the Rocky Mountains, that terminates at the north end of the Big Belt Mountains uplift. In part of this area the front of the zone of major thrusting is a huge anticline—the Beartooth uplift—strongly overturned plainsward, broken by the Beartooth slice thrust and segmented by transverse faults, the exposed thrusting largely disappearing beneath the extensive and lofty lava flows southwest of Cody.[19] That major inter-basin

[18] Arthur Bevan, "Rocky Mountain Front in Montana," *Bull. Geol. Soc. America*, Vol. 40, No. 2 (1929), pp. 427–56.

[19] John T. Rouse, "Genesis and Structural Relationships of the Absaroka Volcanic Rocks, Wyoming," *Bull. Geol. Soc. America*, Vol. 48, No. 9 (1937), pp. 1257–96.

———, "Structural and Volcanic Problems in the Southern Absaroka Mountains, Wyoming," *ibid.*, Vol. 51, No. 9 (1940), pp. 1413–28.

thrusting and subsidiary intra-basin structures are present in the middle Rocky Mountains (Fig. 2) is brought out by the many intensive, extensive, and important structural researches being carried out therein, principally by the Yellowstone-Bighorn Research Association under the supervision of W. T. Thom and associates.

The frontal part of the arc of major eastward thrusting is well displayed in western Wyoming and adjacent parts of Idaho and Utah by several north-south overthrusts and associated parallel folds. The Darby overthrust in western Wyoming and southeastern Idaho is approximately 125 miles long and locally has carried Mississippian strata over Upper Cretaceous strata, the horizontal displacement being perhaps more than 15 miles and the throw (stratigraphic ?) as much as 20,000 feet. The wide Absaroka overthrust next west has a known length of about 200 miles and has a throw (stratigraphic ?) perhaps exceeding 20,000 feet. The notable Bannock overthrust is at least 270 miles long and also relatively wide. The Putnam overthrust has a known length of 20 miles, bringing Cambrian and Ordovician strata into contact with Pennsylvanian or Triassic beds, and the Crawford overthrust throws Carboniferous strata against Cretaceous or Tertiary beds.[20]

The great eastward-tilted Willard overthrust near Ogden, Utah, has carried pre-Cambrian quartzites over Cambrian shales and sandstones, which rest on Archean gneisses. It is now believed that the movement along the Willard overthrust belt was from west to east and that its eastward dip is a secondary feature.[21] The length of this overthrust belt is unknown, for its northwest extension is cut off by the great Wasatch normal fault trending along the west front of the Wasatch Mountains. It is also believed that the large eastward-dipping overthrusts in rocks of Cambrian and Mississippian age in the Cottonwood Canyon and Park City districts, about 40 miles south of Ogden, are secondary features and that the original movement was from west to east.[22]

In the southern Wasatch Mountains, observable overthrusting and overturning are integral parts of the structure south to Nephi,[23] south of which in parts of southwestern Utah and northwestern Arizona they are probably obscured by late

[20] The descriptions of thrust faulting in this paragraph are from: G. R. Mansfield, "Geology, Geography, and Mineral Resources of Part of Southeastern Idaho," *U. S. Geol. Survey Prof. Paper 152* (1927), p. 381.

See also:

A. R. Schultz, "Geology and Geography of a Portion of Lincoln County, Wyoming," *U. S. Geol. Survey Bull. 543* (1914).

A. C. Veatch, "Geography and Geology of a Portion of Southwestern Wyoming," *U. S. Geol. Survey Prof. Paper 56* (1907).

[21] Philip B. King, "An Outline of the Structural Geology of the United States," *XVI Inter. Geol. Congress Guidebook 28* (1932), p. 35.

[22] Philip B. King, *op. cit.*, p. 36.

Note: For an excellent summary of the geology of the Salt Lake region, see John M. Boutwell *et al.*, "The Salt Lake Region," *XVI Inter. Geol. Congress Guidebook 17*, Excursion C-1 (1932).

[23] Armand J. Eardley, "Structure and Physiography of the Southern Wasatch Mountains, Utah," *Michigan Acad. Sci. Arts and Letters*, Vol. 19 (1933), Map 11.

Pliocene, Pleistocene, and Recent normal faults lying in the structural transition zone between the relatively stable Colorado Plateaus and that region of major overthrusting—the Great Basin. A continuation southwestward of the major arc of thrusting is indicated by the Tertiary thrusts in the southwest corner of Utah.[24]

OUTER ZONE OF MAJOR FOLDING

The north end of the easternmost or outer zone of folding in the Rocky Mountains lies where the major, asymmetric Big Belt and Little Belt uplifts plunge beneath the plains south and southwest of Great Falls, Montana, north of which, as previously mentioned, the Rocky Mountain Front continues into Canada with sharp demarcation caused by movements and differential erosion along the Lewis and other overthrust faults.

Although the Big Belt Mountains uplift continues the main structural axis of the Front Ranges northwestward to Missouri River, the Little Belt Mountains uplift seems to be a slightly western anticlinal offset segment of a conspicuous structural salient—the Big Snowy anticlinorium—which trends east-southeast in the Great Plains.[25] These two uplifts are separated by the complexly faulted Crazy Mountain syncline, the northern part of which is occupied by Tertiary volcanics comprising the lofty (11,175 feet) Crazy Mountains.

The Pryor Mountains in southern Montana consist of four major and three minor elevated, rotated, folded, and faulted segments, each uptilted at the northeastern corner and forming one of the asymmetric "trap-door" types of uplifts which are significant and characteristic features of the Central Rockies.[26]

The Big Horn Mountains (maximum altitude, 13,165 feet), and the westward extensions, the Bridger Mountains, the Owl Creek Mountains, and others are characterized strikingly by segments of alternating southwest and northeast thrusting and overturning.[27]

Other major uplifts lying either entirely in or mostly in the outer zone of folding in Wyoming are the huge Wind River Mountains uplift (maximum altitude

[24] C. E. Dobbin, "Geologic Structure of St. George District, Washington County, Utah," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 2 (1939), pp. 129–33.

[25] C. T. Lupton and Wallace Lee, "Geology of the Cat Creek Oil Field, Fergus and Garfield Counties, Montana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 2 (1921), p. 269.
W. T. Thom, Jr., "The Relation of Deep-Seated Faults to the Surface Structural Features of Central Montana," *ibid.*, Vol. 7, No. 1 (1923), p. 9.

[26] D. L. Blackstone, Jr., "Structure of the Pryor Mountains, Montana," *Jour. Geology*, Vol. 48, No. 6 (1940), pp. 590–618.

[27] Rollin T. Chamberlin, "Diastrophic Behavior Around the Big Horn Basin," *Bull. Geol. Soc. America*, Vol. 50, No. 12, Pt. 2 (1939), p. 1903.
John R. Fanshawe, "Structural Geology of Wind River Canyon Area, Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 10 (1939), pp. 1439–92.
Leland Horberg, Vincent Nelson, and Victor Church, "Structural Types and Trends in Central Western Wyoming," *Bull. Geol. Soc. America*, Vol. 51, No. 12, Pt. 2 (1940), p. 1930.
John David Love, "Thrust Faulting at the Southern End of the Big Horn Mountains, Wyoming," *ibid.*, p. 1934.
William G. Pierce, "Heart Mountain and South Fork Thrusts, Park County, Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 11 (1941), pp. 2021–45.

13,785 feet),[28] which is thrust westward,[29] the faulted Gros Ventre Mountains, the Sweetwater (Pathfinder) uplift,[30] which is now represented surficially mainly by a line of relatively low granite knobs overlapped by Tertiary strata, the faulted Rawlins uplift,[31] and the sharp, asymmetric anticlinal Laramie Mountains (maximum altitude, 10,272 feet).[32]

The broad, open Uinta Mountains uplift (maximum altitude, 13,498 feet) in northeastern Utah and vicinity is the largest and longest east-west trending range in the western hemisphere.[33] It is cut and bordered by several long, high-angle faults with major displacements, one of which—the Uinta fault—lies just south of the Clay Basin gas field.

The outer zone of folding in Colorado and northern New Mexico is featured by several uplifts, such as the Front Range, the Wet Mountains, and the Sangre de Cristo Mountains, that are rejuvenated members of Paleozoic mountains. The Front Range uplift[34] is a regional anticline, with subordinate northwest-trending *en échelon* folds on its flanks and with many northwest-trending normal and reverse faults on its east side, that rose on the site of the Carboniferous Colorado geanticline. Behind the Front Range are more or less high (Mt. Elbert, 14,431 feet) continuous, parallel, arcuate faulted uplifts, such as the Park Range, the Sawatch Mountains, and others, which, with the Uinta Mountains, bend around the Colorado Plateaus.[35]

The Sangre de Cristo Mountains in southern Colorado and vicinity are largely a complexly folded sedimentary belt adjacent to downwarped intermontane basins that are bordered by late Tertiary or early Pleistocene high-angle faults—

[28] E. B. and C. C. Branson, "Geology of Wind River Mountains, Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 1 (1941), pp. 120–51.

[29] Charles Laurence Baker, "Westward Overthrusting in Wind River Mountains, Wyoming," *ibid.*, Vol. 49, No. 12, Pt. 2 (1938), p. 1865.

[30] C. J. Hares, "Anticlines in Central Wyoming," *U. S. Geol. Survey Bull. 641* (1916), pp. 249–50.
T. S. Lovering, "The Rawlins, Shirley, and Seminoe Iron-Ore Deposits, Carbon County, Wyoming," *ibid., Bull. 811* (1930), p. 209.

[31] C. E. Dobbin, H. W. Hoots, and C. H. Dane, "Geology and Oil and Gas Possibilities of the Bell Springs District, Carbon County, Wyoming," *ibid., Bull. 796* (1928), pp. 187–90.

[32] A. C. Spencer, "Economic Geology of the North Laramie Mountains, Converse and Albany Counties, Wyoming," *ibid., Bull. 626* (1916), pp. 47–81. Geologic map after N. H. Darton and others, 1907.
N. H. Darton, Eliot Blackwelder, and C. E. Siebenthal, "Laramie-Sherman, Wyoming," *ibid., Geol. Atlas Folio 173* (1910).

[33] J. D. Forrester, "Structure of the Uinta Mountains," *Bull. Geol. Soc. America*, Vol. 48, No. 5 (1937), pp. 631–66.

[34] See also:
R. H. Beckwith, "Structure of the Southwest Margin of the Laramie Basin, Wyoming," *ibid.*, Vol. 49, No. 10 (1938), pp. 1515–44.
———, "Structure of the Elk Mountain District, Carbon County, Wyoming," *ibid.*, Vol. 52, No. 9 (1941), pp. 1445–86.

[35] Walter H. Bucher, *The Deformation of the Earth's Crust*, Princeton University Press (1933), pp. 78–81.
W. S. Burbank and T. S. Lovering, "Relation of Stratigraphy, Structure, and Igneous Activity to Ore Deposition of Colorado and Southern Wyoming," *Amer. Inst. Min. Met. Eng.*, Lindgren Volume (1933), pp. 272–316.

both normal and overthrust—in fact, the San Luis Valley on the west is probably a type of basin-and-range structure.[36] These mountains were re-elevated near the site of a Paleozoic range that was folded at about the same time as the Ouachita Mountains and the Arbuckle Mountains of Oklahoma.

The outer zone of folding in the Rocky Mountains dies out near Santa Fe, New Mexico, abutting directly against the tilted north-south block mountain ranges and faulted synclinal valleys characteristic of the Basin-and-Range Province of central New Mexico.

The major structural downwarps in the outer zone of folding occur in Wyoming, and include the Wind River, Laramie, Hanna, Shirley, and Green River basins, the last named including the Bridger and Washakie subsidiary basins. All these basins have rather undisturbed Tertiary beds either wholly or partly at the surface—in fact, the Hanna Basin contains as much as 20,000 feet of latest Cretaceous and early Tertiary coal-bearing strata. In contrast, the intermontane basins in this closely folded zone in Colorado and New Mexico are probably much faulted.

COLORADO PLATEAUS

Although the strata in the Colorado Plateaus are in most places either flat or gently tilted, there are some rather broad uplifts and downwarps, such as the Zuni anticline of northwestern New Mexico, the Defiance uplift of northeastern Arizona, the Uncompahgre uplift of southwestern Colorado, and the San Rafael swell of southeastern Utah—all rejuvenated—and the Uinta, San Juan, and Black Mesa structural basins, and lesser upwarps, downwarps, abrupt monoclines, linear zones of faulting and conspicuous laccoliths.[37] The west border of the plateaus is featured by the north-south-trending belt of normal faults at the eastern margin of the Great Basin.

Origin of Producing Structures

Although geologists generally agree on the rôle played by local structure in oil and gas accumulation in the Rocky Mountain region, there is disagreement here, as elsewhere, on the origin and nature of the forces responsible for both regional and local structures. It can be conjectured that certain regional structures—such as those in eastern Montana—resulted from the deformation of a granitic basement featured by local lines of weakness in pre-Cambrian rocks, and it can be postulated that certain other regional structures were caused by such processes as simple folding under compression, isostatic adjustment, combinations of vertical and tangential forces, ramp-like thrusts in basement

[36] W. S. Burbank and E. N. Goddard, "Thrusting in Huerfano Park, Colorado, and Related Problems of Orogeny in the Sangre de Cristo Mountains," *Bull. Geol. Soc. America*, Vol. 48, No. 7 (1937), pp. 931–76.
Edward C. Cabot, "Fault Border of the Sangre de Cristo Mountains North of Santa Fe, New Mexico," *Jour. Geology*, Vol. 46, No. 1 (1938), pp. 88–105.

[37] A. A. Baker, "Geologic Structure of Southeastern Utah," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 10 (1935), pp. 1472–1507.

rocks, and by underthrusting—all interrelated—without knowing much concerning the distance that the earth can transmit tangential stresses and why—if it does transmit them over long distances—there is not more evidence of the effects throughout these distances. Even more detailed work may not show in what stages of Laramide orogeny the different major and minor structures were formed, what effect torsion may have had in forming all structures, to what extent Laramide structures are superimposed upon older tectonic patterns, and whether many of the major uplifts resulted from wedge uplift and compression, or block elevation and rotation, or the draping of sedimentary beds over the edges of rotated or tilted blocks of the fundamental crystallines, or batholithic intrusion.

Practically all structures producing oil and gas in the Rocky Mountain region are products of Laramide orogeny. That at least one structure (Kevin-Sunburst dome) is rejuvenated, that some resulted from igneous intrusions, that others were made by peculiar and puzzling forms of thrust faulting, and that the large majority are subordinate to major uplifts is clear—all occurring in a region of varied orogenic history now welded into one morphologic unit.[38]

Because of the relatively small areas of most oil and gas structures in the Rocky Mountain region, and particularly as there is little or no drilling in the deep, contiguous structural basins, geological details on the variations in the thickness of beds on the crests of anticlines as compared with that on the extended flanks are scarce. It is known, however, that the relative uplift between some mountains and adjoining basins in Wyoming is as much as 30,000 feet.[39]

REJUVENATED STRUCTURES

The Sweetgrass arch, in northern Montana, is the only important area in the Rocky Mountain region in which oil and gas accumulation is known to be directly related to pre-Laramide folding. The arch originates in the Little Belt Mountains, and plunges northward into Alberta, that portion north of Missouri River being superimposed upon a long, broad arch developed in the Carboniferous and which parallels the present Rocky Mountain Front from Great Falls, Montana, northward beyond Calgary, Alberta. The lines of weakness engendered by the development of this ancient arch—the Calgary-Great Falls arch—localized the position of Kevin-Sunburst dome and South arch, both of which form the Sweetgrass arch proper and are characterized by minor cross-folds. The lack of evidence of strong compressive folding over the main part of the arch indicates that its present structure was caused by dominantly vertical forces during Laramide orogeny.

[38] Note: For a discussion and a depiction of relations of productive areas to paleogeography in the Rocky Mountain region, see Ross L. Heaton, "Stratigraphy Versus Structure in Rocky Mountain Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 21, No. 10 (1937), pp. 1246–67.

[39] For a general discussion of geologic conditions in the principal structural basins of the Rocky Mountain region, see C. E. Dobbin *et al.*, "Possible Future Oil Provinces in Rocky Mountain Region," *Possible Future Oil Provinces of the United States and Canada* (Amer. Assoc. Petrol. Geol., 1941), pp. 37–75.

TERTIARY IGNEOUS INTRUSIONS

The three producing structures on the north side of the laccolithic Sweetgrass Hills, Montana, namely, Whitlash, Bear's Den and Flat Coulee,[40] were apparently developed by or are closely related to igneous intrusive masses of the Hills, probably resulting from upthrusts of deep igneous plugs. The proximity of the small Guinn dome to the laccolithic Little Rocky Mountains suggests a similar origin for that feature. That the broad Bowdoin dome[41] at the northeast is also of very deep igneous origin is strongly indicated by its general shape, its association with other known igneous features in the zone of igneous mountains featuring northern Montana east of Sweetgrass arch, by the positive gravity anomaly near Hinsdale, by the hot water in the dome at a depth of about 3,200 feet, and by a geothermal gradient about 50 per cent greater than at Kevin-Sunburst dome.

THRUST-FAULTED STRUCTURES

In the peculiar Bearpaw Mountains shallow thrust-fault zone in north-central Montana are at least six known gas-containing structures. The zone surrounds the volcanic mountains and extends southwestward to the Highwood Mountains.[42] It is characterized by almost horizontal Upper Cretaceous strata, which locally are buckled in a series of long, narrow anticlines, many of which have complex shallow thrust fault relations. Drilling in the faulted zone has shown that the thrust faulting is confined to weak Upper Cretaceous and early Tertiary formations. The fault pattern suggests that the fault structures were formed during the middle Tertiary epoch of volcanic activity in the Bearpaws by the slipping plainsward of formations in the upper part of the Colorado shale resulting in the compression and thrust faulting of these formations in the plains. Although certain field evidence to support this theory is seemingly lacking, there is apparently no better explanation for the thrust faulting than the preceding one, offered by Reeves[43] after intensive study of the area.

[40] C. E. Erdmann, "Preliminary Structure Contour Map of the Bear's Den-Flat Coulee-Whitlash Districts, North Central Montana," *U. S. Geol. Survey* (1930).

[41] C. E. Erdmann and J. R. Schwabrow, "Structure Contour Map of the Central Part of Bowdoin Dome, Phillips and Valley Counties, Montana," *U. S. Geol. Survey* (1933).

[42] Esper S. Larsen, "Petrographic Province of Central Montana," *Bull. Geol. Soc. America*, Vol. 51, No. 6 (1940), pp. 887–948. See also Vol. 52, No. 11 (1941), pp. 1733–1828 and Vol. 52, No. 12, Pt. 1, pp. 1829–68.

William T. Pecora, "Structure and Petrology of the Boxelder Laccolith, Bearpaw Mountains, Montana," *ibid.*, Vol. 52, No. 6 (1941), pp. 817–54.

W. G. Pierce and C. B. Hunt, "Geology and Mineral Resources of North-Central Chouteau, Western Hill and Eastern Liberty Counties, Montana," *U. S. Geol. Survey Bull. 847* (1937), pp. 253–57.

Frank Reeves, "Geology and Possible Oil and Gas Resources of the Faulted Area South of the Bearpaw Mountains, Montana," *ibid., Bull. 751* (1924), pp. 97–103.

———, "Thrust-Faulting and Oil Possibilities in the Plains Adjacent to the Highwood Mountains, Montana," *ibid., Bull. 806* (1929), pp. 167–85.

[43] Frank Reeves, *op. cit.*

Bartram and Hupp[44] have classified asymmetrical, steep-sided structures in Wyoming and northern Colorado as overthrust and underthrust types, stating that:

> As this thrust force from the west moved through the fairly competent rocks of Wyoming, it of course met an almost equal resistance. The result was that the rocks were folded into a series of large anticlines (Fig. 3) that are the present mountains, and large synclines that are the basins. Flanking the large folds are the smaller anticlines on which the oil and gas fields occur (p. 1279).

The Labarge oil field, in southwestern Wyoming (Fig. 5), is a low dome on an anticline lying two miles east of the Darby overthrust, which has pushed early Paleozoic limestones over Upper Cretaceous beds. Bartram and Hupp[45] state that the vertical displacement is more than 20,000 feet and that the field is on a complexly faulted structure resembling an unsymmetrical anticline. Further data on the geologic structure at and near the Labarge field are given by Bertagnolli.[46]

Other productive structures, outside of Wyoming and north-central Colorado, that lie relatively close to major overthrusts, are the Dry Creek field in southern Montana (Fig. 4), and the Canon City and Florence fields, near central Colorado (Fig. 9).

SUBORDINATE STRUCTURES

The northernmost oil and gas structures in the United States that are clearly subordinate to a major uplift are the Cat Creek, Armells, and Devils Basin fields, which lie on the Big Snowy anticlinorium, only the first one being of relative importance.

The Big Snowy anticlinorium includes the huge asymmetric Big Snowy Mountains anticline,[47] the laccolithic Judith Mountains and Moccasin Mountains, Porcupine dome and many other smaller structural features that impart a bilateral symmetry to the plains and modify the otherwise relatively simple structure of that region. The Cat Creek anticline and Devils Basin dome roughly bound a rectangular block about 50 miles long and 40 miles wide, which is tilted eastward and marked along its northern and southern margins by belts of highly inclined strata, just inside of which are *en échelon* series of elliptical and asymmetric domes that vary greatly in size and structural closure.[48]

Although the Big Snowy anticlinorium may be of deep-seated origin in which

[44] John G. Bartram and J. E. Hupp, "Subsurface Structure of Some Unsymmetrical Anticlines in the Rocky Mountains," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (1929), pp. 1275–89.

[45] John G. Bartram and J. E. Hupp, *op. cit.*, pp. 1284–85.

[46] A. J. Bertagnolli, Jr., "Geology of Southern Part of LaBarge Region, Lincoln County, Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 9 (1941), pp. 1729–44.

[47] Frank Reeves, "Geology of the Big Snowy Mountains, Montana," *U. S. Geol. Survey Prof. Paper 165* (1931), pp. 135–49.

[48] ———, "Geology of the Cat Creek and Devils Basin Oil Fields and Adjacent Areas in Montana," *U. S. Geol. Survey Bull. 786* (1927), pp. 39–95.

igneous agencies played an important part and although its circular domes are most surely due to igneous origin, the great thinning (as much as 30 per cent) of the Upper Cretaceous shale formations on the flanks of most of the elongate marginal domes suggests that these transversely faulted, asymmetric elliptical domes, the belts of *en échelon* faults, and the Big Snowy Mountains are largely due to unequal tangential compression.

Some of the small oil and gas fields in southern Montana—Dry Creek, Big Lake, and Mosser—fall in that area of block elevation, rotation, and faulting, dominated by the Pryor Mountains uplift, whereas Soap Creek and Hardin are structural features subordinate to the Big Horn Mountains uplift—a probable product of uplift and compression.

The Cedar Creek anticline, approximately 100 miles long, is seemingly an offset continuation of the Black Hills uplift in which block elevation and rotation have played a relatively large rôle.[49]

With few exceptions—such as the Baxter Basin gas fields, and the small Virgin oil field in southwestern Utah, the Bueyeros gas field in northeastern New Mexico, and the Greasewood[50] oil field in northeastern Colorado—the oil and gas structures in the Rocky Mountain region south of Montana seem clearly satellite to major uplifts, some of which in Colorado, New Mexico, and Utah are, as previously stated, rejuvenated Carboniferous uplifts. As the producing structures are on the peripheries of subordinate structural basins, it is logical to assume that they were progressively formed from areas of maximum stress intensity—the major uplifts—toward the areas of less stress intensity—the structural basins—as suggested by the mountainward, intermediate, and basinward anticlines in the Big Horn Basin, Wyoming. Apparently few, if any, of the producing structures south of Montana resulted from Tertiary intrusions.

Types of Producing Structures

Fifty-eight per cent of all the oil and gas fields in the Rocky Mountain region are anticlines and domes whose producing areas are either not faulted or are only slightly faulted at the surface; 26 per cent are anticlines and domes, faulted at the surface, and fault blocks; 14 per cent are monoclines and structural terraces; and 2 per cent are plunging anticlines and structural noses.

[49] F. W. DeWolf and W. W. West, "Stratigraphic Studies of Baker-Glendive Anticline, Eastern Montana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 4 (1939), pp. 461–75.

C. E. Dobbin, C. E. Erdmann and R. M. Larsen, "Geologic and Structure Contour Maps of the Cedar Creek Anticline, Montana and North Dakota," *U. S. Geol. Survey* (1935).

O. A. Seager, "Test on Cedar Creek Anticline, Southeastern Montana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26, No. 5 (1942), pp. 861–64.

W. T. Thom, Jr., R. T. Chamberlin, and W. H. Bucher, "Regional Structural Relations of the Yellowstone-Beartooth-Big Horn Region," *XVI Inter. Geol. Congress Guidebook 24* (1932), p. 4.

[50] C. S. Lavington, "Greasewood Oil Field, Weld County, Colorado," *Stratigraphic Type Oil Fields* (Amer. Assoc. Petrol. Geol., 1941), pp. 19–42.

UNFAULTED ANTICLINES AND DOMES

MONTANA[51]

Although there are 10 unfaulted structures in Montana that have produced oil and gas, only 3 are of relative economic importance; namely, Kevin-Sunburst, Bowdoin, and Cedar Creek (Baker-Glendive), the two last-named producing gas from Upper Cretaceous sandstones. The remaining 7 fields in this classification are either shut in, abandoned, or produce small amounts of oil or gas intermittently.

Bowdoin dome is the largest producing structure in the Rocky Mountain region, being a very broad, low, almost circular uplift about 66 miles long and 62 miles across at the widest place with a total regional closure of about 700 feet. The central part of the dome exhibits two "highs," each having about 100 feet of closure.

Kevin-Sunburst dome is a broad feature about 36 miles long and 36 miles wide on Sweetgrass arch with a total closure of 850 feet.

The Cedar Creek anticline is a sharp, unsymmetrical anticline about 100 miles long that produces commercial amounts of gas from several subsidiary domes along its crest.

The seven rather unimportant unfaulted oil and gas fields in Montana range in structural definition from low folds with less than 125 feet of structural closure, such as Bannatyne (abandoned), Flat Coulee, and Big Lake to sharp, well defined domes with relatively large structural closure, namely, Whitlash (500 feet) and Soap Creek (800 feet).

WYOMING[52]

In Wyoming, oil and gas have been produced in varying amounts from 63 unfaulted or slightly faulted anticlines and domes that vary to the extreme in shape, size, and amount of structural closure. There are gentle, low domes, such as Badger Basin, Golden Eagle, Billy Creek, East Mule Creek, and others; there are simple, asymmetric, elongate anticlines, such as Rock Creek; there are broad, oval mountainward anticlines, such as Mahoney; there are asymmetrical domes with relatively large amounts of structural closure, for example, Medicine Bow (2,900+ feet, Fig. 6), Little Buffalo Basin (1,600 feet), Shoshone (1,400 feet, Fig.

[51] John G. Bartram and C. E. Erdmann, "Natural Gas in Montana," *Geology of Natural Gas* (Amer. Assoc. Petrol. Geol., 1935), pp. 245–76.

C. E. Dobbin and C. E. Erdmann, "Structure Contour Map of the Montana Plains," *U. S. Geol. Survey* (1932). Revised in 1935.

———, "Geologic Occurrence of Oil and Gas in Montana," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), pp. 695–718.

Eugene S. Perry, "Natural Gas in Montana," *Montana Bur. Mines and Geology Memoir 3* (1937).

[52] See also:

Ralph H. Espach and H. Dale Nichols, "Petroleum and Natural Gas Fields in Wyoming," *U. S. Bur. Mines Bull. 418* (1941).

E. W. Krampert, "Characteristics of the Oil and Gas Fields of the Rocky Mountain District, Part I, Wyoming," *Mines Magazine*, Vol. 31, No. 9 (1941), pp. 430–40; 481–82.

C. E. Schoenfelt, "Oil and Gas in the Rocky Mountain District in 1941," *Amer. Inst. Min. Met. Eng.*, Petrol. Div., Vol. 146 (1942), pp. 412–20.

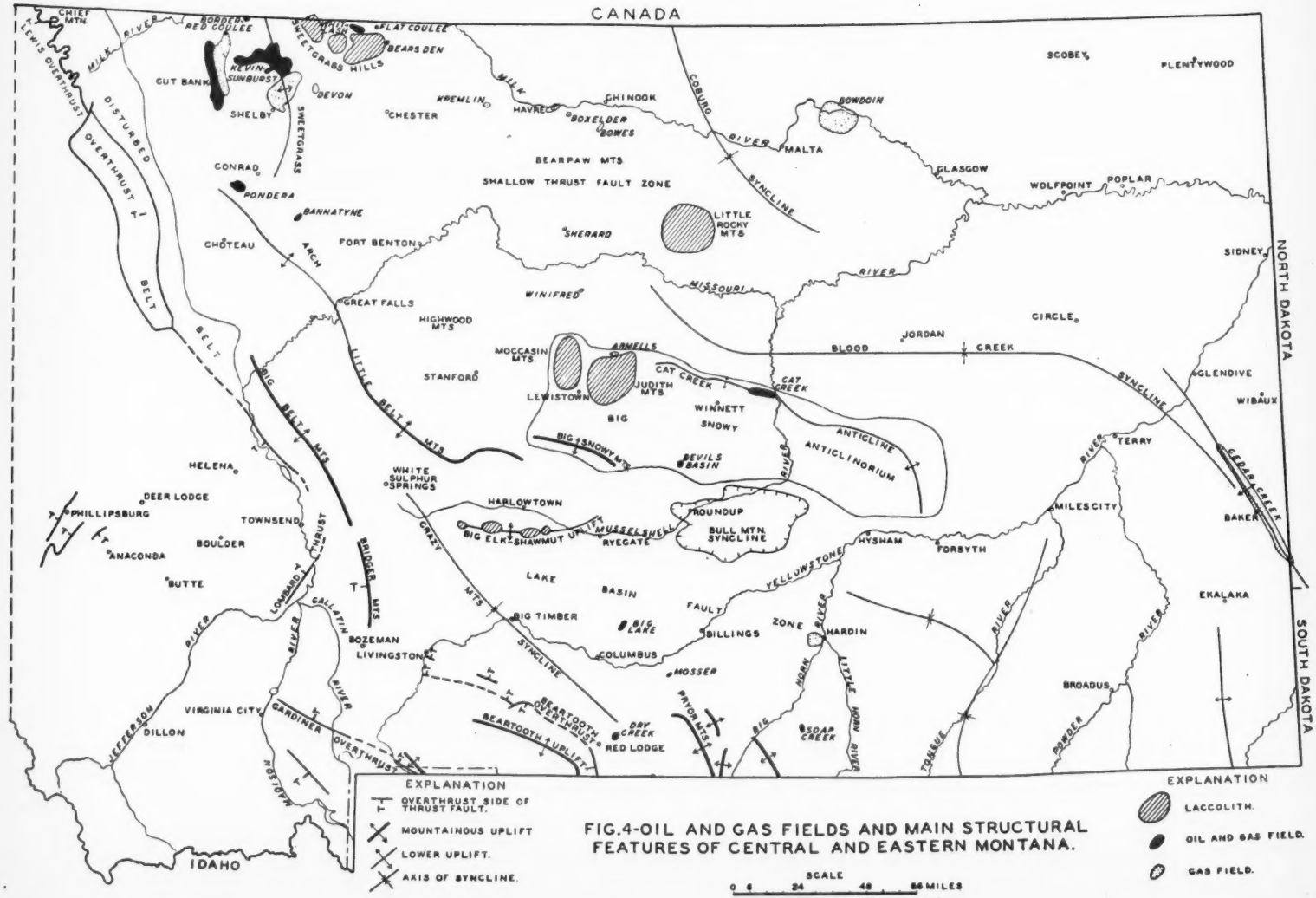


FIG. 4-OIL AND GAS FIELDS AND MAIN STRUCTURAL FEATURES OF CENTRAL AND EASTERN MONTANA.

TABLE I

Surface Types of Oil and Gas Fields in Montana

A. Anticlines and domes whose productive areas are either not faulted or only slightly faulted.

Field and Year of Discovery	Location (Townships and Ranges)	Principal Producing Zones						Remarks
		Age	Formation	Member	Contents	Gravity A.P.I. at 60° F.	Depth (Feet)	
Kevin-Sunburst 1922	32–36 N., 1–4 W.	L. Cretaceous U. Jurassic Mississippian	Kootenai Ellis Madison	Sunburst sand Stray sand Top[a]	Oil and gas	34–38 38 31[b]–37	1100–1735 1200–1600 1340–1900	Broad dome on Sweetgrass arch with total closure of 850 feet. Kootenai production limited by sand irregularities. Madison accumulation controlled largely by erratic porosity caused by pre-Jurassic weathering of limestone surface.
Bannatyne 1927	25–26 N., 1 E.	U. Jurassic	Ellis	Emrick sand	Oil and a little gas	23–27[b]	1445	Production controlled by slight cross-folding on Sweetgrass arch. Emrick sand 30–75 feet thick and enclosed in black, calcareous shale, which is probably the source of the oil. Field abandoned.
Whitlash 1918	37 N., 3–4 E.	U. Cretaceous L. Cretaceous U. Jurassic	Colorado Kootenai Ellis	Blackleaf[a] Basal sand Basal sand	Oil and gas Gas and water	39 36	1525 2030 2300	Sharp dome with 500± feet of closure resulting from upthrust of a deep-seated igneous plug in Sweetgrass Hills uplift.
Flat Coulee 1928	37 N., 5 E.	L. Cretaceous U. Jurassic	Kootenai Ellis	Basal sand Basal sand	Oil Gas	31	2600	Small dome with about 100 feet of closure near the Sweetgrass Hills uplift and apparently of igneous origin.
Bowdoin 1912	30–33 N. 31–35 E.	U. Cretaceous	Colorado	Bowdoin sand Phillips sand	Gas		740 1000	Broad dome with 700 feet of regional closure probably caused by deep-seated igneous intrusion. Has two "highs" with about 100 feet of closure each. Gas is in sand lentils in marine shale.
Devils Basin 1919	11 N., 24 E.	Mississippian	Heath	Van Duzen sand	Oil	25[b]	1160	Dome in Big Snowy anticlinorium. Oil is in lenticular sands, sandy shale, or limestone.
Big Lake or Lake Basin 1922–24	1 N., 21 E.	U. Cretaceous	Eagle Frontier		Gas		1130–1415	Gentle fold with 120 feet of closure. A little gas in the Claggett shale.
		L. Cretaceous	Cloverly	Greybull ss.	Oil and gas	45	3795–3960	
Soap Creek 1921	6 S., 32 E.	Pennsylvanian Mississippian	Amsden Madison	Top	Oil	19[b]	1700	Asymmetrical dome with total closure of 800 feet. Oil is trapped in dome by large volumes of water under heavy artesian head. A little oil in the Tensleep sandstone.
Cedar Creek[c] or Baker-Glendive 1914	4–14 N., 55–62 E. (Montana) and 130–133 N. 106–107 W. (So. Dakota)	U. Cretaceous	Judith River (?) Eagle (?)		Gas		800 1500	Asymmetric anticline more than 100 miles long. Gas and oil are in low domes along major anticlinal axis. Judith River (?) and Eagle ss. (?) production is in thin, lenticular, shaly sands.
		Mississippian	Madison		Oil	27[b]	6815	
		Ordovician			Oil saturation		8659	Pre-Eagle oil not in commercial amounts.
Guinn 1931	24 N. 24 E.	U. Cretaceous	Eagle		Gas		435–848	Almost circular laccolithic dome. Somewhat faulted.

B. Faulted anticlines and domes, and fault blocks.

Bowes 1924	31–32 N. 19 E.	Upper					655–1078	Havre field abandoned.
Havre 1914	32–33 N. 16–17 E.						1050	
Boxelder 1916	32 N. 17 E.						940–1319	

Kremlin 1921	32–33 N. 12 E.	Cretaceous	Eagle		Gas		1050	Small, faulted anticlines and fault blocks in the Bearpaw Mts. shallow thrust fault zone.
Sherard or Sand Creek 1923	25 N., 17 E.						1735	
Winifred 1935	21–22 N., 17–18 E.						390–566	
Armells or Cone Butte 1924	17 N., 20 E.	L. Cretaceous	Kootenai				1322	Faulted dome in Big Snowy anticlinorium.
Cat Creek 1920	15 N., 29–30 E.	U. Cretaceous	Colorado	First Cat Creek sand[a]	Oil	50	800–1400	Two faulted domes on an anticline in the Big Snowy anticlinorum. No gas.
		L. Cretaceous	Kootenai	Second Cat Creek sand		48	1000–1600	
Mosser 1936	3 S., 24 E.	L. Cretaceous	Cloverly	Greybull ss.		22[b]	1000	Closure of several hundred feet against the Fromberg fault.
Dry Creek 1929	7 S., 21–22 E.	U. Cretaceous	Claggett Eagle Frontier	Parkmann ss. Lower sand Second sand	Gas		2290 4360	Extremely faulted dome with about 1500 feet of closure. One fault has a throw of about 1,000 feet and several others have 500 feet or more.
		L. Cretaceous	Cloverly	Greybull ss. Pryor congl.	Oil and gas	52	5412	
C. Structural noses.								
Border—Red Coulee 1929	37 N.; 3–4 W. Mont. 1 N.; 16 W. Alta.	L. Cretaceous	Kootenai	Sunburst sand	Gas		2400	Oil and gas accumulation caused by a combination of sand lensing and structural nosing.
				Cut Bank sand	Oil	32	2520	
Bear's Den 1923	36 N., 5–6 E.	U. Cretaceous	Colorado	Blackleaf	Gas		1600	Small anticlinal nose in the Sweetgrass Hills uplift. Closure due to metamorphism, igneous intrusion, and sealing of sand lenses by shale. Some faulting.
		L. Cretaceous	Kootenai		Oil and gas	40	2200	
D. Structural terraces.								
Pondera 1927	27 N., 4 W.	Mississippian	Madison	Top 40 feet	Mostly oil	33[b]	2000	Oil accumulated in dolomitized limestone made porous by pre-Jurassic weathering.
Hardin 1913	1 S., 32–34 E.	U. Cretaceous	Frontier		Gas		735	Accumulation caused by lenticularity of sands and slight anticlinal folding along Lake Basin-Huntley fault zone. Largely a terrace. Oil in thin sands and sandy shale.
Bow and Arrow 1935	37 N., 1 W. and 1 E.	L. Cretaceous	Kootenai	Sunburst sand			2100	Structural terrace with slight nosing.
E. Monoclines.								
Cut Bank 1926	32–37 N., 5–6 W.	L. Cretaceous	Kootenai	Sunburst sand	Oil locally	38	2840	Monocline on west flank of Kevin-Sunburst dome. Sunburst sand continues eastward. Cut Bank sand feathers out up dip forming a stratigraphic trap. Some accumulation in small structural noses.
				Cut Bank sand[a]	Oil and gas		2900	
Devon 1929	33 N., 1–2 E.	U. Cretaceous	Colorado	Blackleaf	Gas		780	Small gas accumulation in lenticular sands on southeast flank of Kevin-Sunburst dome.

[a] Principal oil zones.
[b] Black in Color.
[c] After O. A. Seager, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26, No. 5 (May, 1942).

TABLE II

Surface Types of Oil and Gas Fields in Wyoming

A. Anticlines and domes whose productive areas are either not faulted or only slightly faulted.

	Field and Year of Discovery	Location (Tps. & Rs.)	Principal Producing Zones					Remarks
			Age	Formation	Contents	Gravity A.P.I. at 60° F.	Depth (Feet)	
Big Horn Basin	Golden Eagle 1921	45 N. 97 W.	U. Cret.	Mesaverde	Gas		3000	Small dome with 350 ft. of closure. Depleted. Gas dry.
	Badger Basin 1930	57 N., 101 W.		Frontier	Oil	47	8500	Gentle dome with about 150 ft. of closure.
	Little Buffalo Basin 1914	47–48 N., 99–100 W.			Gas		1400	Two basinward domes with total closure of about 1,600 ft.
	Enos Creek 1923	46 N., 100 W.					2850	Small, symmetrical, mountainward anticline with 1,000 ft. of closure.
	Walker Dome 1930	46 N., 99 W.					3130	Small, symmetrical dome with about 370 ft. of closure.
	Little Grass Creek 1917	46 N., 99 W.					2730	Small, circular, basinward dome with 600 ft. of closure.
	Kirby Creek 1918	43 N. 92 W.			Oil and gas	41	367	Narrow, asymmetrical, mountainward anticline with small amount of closure.
	Hidden Dome 1918	47–48 N., 90–91 W.				43	1200	Long, narrow anticline with 300 ft. of closure.
	Lamb 1913	51 N., 92–93 W.					650	Symmetrical, basinward dome with about 200 ft. of closure. Uncommercial. Some gas in Muddy sand.
	Torchlight 1913	51 N., 92–93 W.		Mowry		45	500	Elliptical, asymmetrical, basinward dome with about 425 ft. of closure.
	S. Sunshine 1926	46 N., 101 W.	Permian			18[b]	2480	Broad, asymmetrical, mountainward dome with at least 800 ft. of closure.
	Waugh 1934	44–45 N., 97 W.		Embar		28[b]	3780	Sharp, asymmetrical, mountainward dome with 600 ft. of closure.
	Warm Springs 1917	43 N., 93–94 W.				18[b]	850	Two long, asymmetrical, mountainward domes on a major anticline. Closures 300 and 150 ft.
	Lake Creek 1925	43 N., 91 W.				25[b]	3700	Long, narrow, asymmetrical, basinward anticline with about 800 ft. of closure.
	Fourbear 1928	48 N., 103 W.				14[b]	3050	Separate highs on long, sharp, mountainward anticline. Some oil probably occurs in the Embar and Amsden.
	N. Sunshine 1928	47 N., 101 W.				15[b]	3480	Long, sharp, mountainward dome with about 1,500 ft. of closure.

Crystal Creek 1919	54 N., 93 W.	Penn.	Tensleep	Oil	18[b]	724	Two small, slightly faulted asymmetrical domes on a long, narrow anticline. Total closure about 800 ft.
Gooseberry 1937	46–47 N., 100 W.	Permian-Penn.	Embar-Tensleep		22[b]	5900	Mountainward dome with 2,400 feet of closure.
Shoshone 1910	53 N., 101 W.	U. Cret. Permian	Thermopolis Embar		44 19[b]	1083 4500	Sharp, asymmetrical, basinward anticline with 1,400 ft. of closure. Some oil in the Frontier.
Spring Creek 1929	49– 50 N., 101–102 W.	Permian-Penn.	Embar-Tensleep Amsden		16[b]	3810	Two domes on an elongated, mountainward anticline. North dome has about 400 ft. of closure.
Black Mtn. 1922	43 N., 90– 91 W.		Embar-Tensleep		23[b]	3150	Long, narrow, asymmetrical, basinward anticline faulted at southeast end. Closure is about 1,100 ft.
Grass Creek 1914	46 N., 98– 99 W.	U. Cret. U. Jurassic Triassic, etc. Permian-Penn.	Frontier[a] Morrison Chugwater Embar-Tensleep[a]		45 16[b] 18[b] 25[b]	500–1300 1887 3100 3565–4400	Elongated, asymmetrical, basinward dome with about 2,400 feet of closure. Some gas in the Muddy and Greybull sands.
Sheldon 1935	5 N., 2 W. W.R.M.	U. Cret.	Frontier	Gas		2600±	Small, asymmetrical dome.
Plunkett 1909	1 S., 1 E., W.R.M.		Mowry	Oil	42	450	At north end of long, sharp, asymmetrical anticline. Mostly an anticlinal nose.
Big Sand Draw 1918	32 N., 95 W.		Frontier[a]	Gas		2500	Sharply folded, elongated, asymmetrical anticline with very large amount of closure.
		L. Cret.	Cloverly			4300	
Beaver Creek 1938	33– 34 N., 96 W.	U. Jurassic	Morrison			8230	Large dome with moderate amount of closure. Showed gas in Frontier and Cloverly.
Spindletop 1922	30 N., 81 W.		Sundance	Oil	21[b]	1025	A steep-sided dome with a rather flat top. Total closure about 1,000 ft. Showings of oil in Embar.
Bolton Creek 1920	29 N., 81 W.				22[b]	1100	Dome with about 600 ft. of closure. Minor faulting in producing area. Abandoned.
		Permian	Embar		32[b]	2100	
Sage Creek 1909	1 N., 1 W., W.R.M.	Triassic and Permian	Chugwater		22[b]	750	Asymmetrical anticline.
Maverick Springs 1917	6 N., 2 W., W.R.M.	Permian	Embar		21[b]	1500	Long, asymmetrical dome with 600 ft. of closure. Some oil in the Tensleep.
Circle Ridge 1923	6 N., 2–3 W. W.R.M.	Permian and Penn.	Embar and Tensleep		24[b]	170–1040	Small dome closed on southwest by fault.
Lander (Hudson) 1909	2 S., 1–2 E. W.R.M. 33 N., 99 W.				22[b]	1000+	Local domes on the long, partially overturned Lander anticline.
Dallas 1884	32 N. 99 W.				22[b]	1000	Dallas has at least 300 ft. of closure, and Lander and Derby at least 1,500 ft. each.
Derby 1921	31 N. 98 W.				22[b]	1000	

Wind River and Shirley Basins

TABLE II (*Cont.*)

Powder River Basin and Vicinity

Field and Year of Discovery	*Location (Tps. & Rs.)*	*Principal Producing Zones*					*Remarks*
		Age	*Formation*	*Contents*	*Gravity A.P.I. at 60° F.*	Average *Depth (Feet)*	
Boone 1923	35 N. 85 W.	U. Cret.	Steele	Gas		1600	Sharp, elongated, asymmetrical anticline. A little gas in the Frontier. About 100 ft. of closure.
Billy Creek 1923	48 N. 82 W.		Frontier	Gas and oil	20	3200	Low dome with 450 ft. of closure. Gas is very dry.
Midway 1931	35 N. 79 W.		Frontier Thermopolis	Oil	31	5150 5900	Elliptical dome with more than 1,000 ft. of closure.
Iron Creek 1917	32 N. 82 W.		Dakota (?)	Oil and gas	28	700	Sharp, symmetrical dome with about 500 ft. of closure.
Ant Hills 1927	37 N. 63 W.	L. Cret.	Fall River	Oil	34	3945	Small circular dome with 125 ft. of closure.
Cole Creek 1938	35 N. 77 W.	U. Cret.	Steele		35	4500	Large, symmetrical dome with 500 ft. of closure. Oil saturation in Frontier, Dakota (?) and Lakota.
East Mule Creek 1919	39 N. 60–61 W.	L. Cret.	Lakota		32	1400	Low, symmetrical dome with about 250 ft. of closure. Some oil in the Fall River and Minnelusa ([23b])
Poison Spider 1917	33 N. 82–83 W.	U. Jurassic	Sundance	Oil and gas	21[b]	1350	Symmetrical dome with about 175 ft. of closure.
Notches 1923	37 N. 85 W.	Penn.	Tensleep	Oil	23[b]	2750	Small, asymmetrical dome with about 700 ft. of closure.
N. Casper Creek 1925	36–37 N. 81–82 W.				22[b]	3200	Simple, asymmetrical dome with about 1,000 ft. of closure Some gas in the Mowry.
Lance Creek 1918	35–36 N. 64–65 W.	L. Cret. U. Jurassic Penn.	Fall River Sundance Minnelusa[a]	Oil and gas	42 38[b]–47 42[b]–45	3200 3800 4400–5200	Broad dome with about 650 ft. of closure on an elongated, asymmetrical anticline. Severely faulted on west flank. Some oil in the Wall Creek and Newcastle (Muddy) sands and some gas in the Lakota.
West Mule Creek 1927	39–40 N. 61 W.	Cret. Penn.	Dakota gr.[a] Minnelusa	Oil	35 34[b]	275 2700	Elongated, asymmetrical dome with 600± ft. of closure.
S. Casper Creek 1919	33–34 N. 83 W.	U. Jurassic Penn.	Sundance Tensleep	Gas Oil	15[b]	1350 2430	Two domes with about 300 ft. of total independent closure.

Laramie Basin and Vicinity	Simpson Ridge 1923	21 N. 80 W.	U. Cret.	Mesaverde	Oil	22	800	Small, sharp, asymmetrical, slightly faulted dome with about 500 feet of closure.
	Big Hollow 1938	15 N. 75 W.		Thermopolis		19[b]	900	Symmetrical dome.
	Quealy 1934	17 N. 76–77 W.	L. Cret.	Cloverly		34	3300	Small, sharply folded, elongated, asymmetrical dome. Some oil in Muddy sand and in the Sundance.
	Allen Lake 1918	23 N. 79 W.	U. Jurassic	Sundance	Gas		2000	Small dome with about 900 ft. of independent closure. Some gas in the Muddy and Cloverly.
	E. Allen Lake 1937	22 N. 78 W.					2000	Small dome.
	Medicine Bow 1935	21 N. 79 W.			Oil and gas	63	5400	Asymmetrical dome with at least 2,900 ft. of total closure. Some oil in the Frontier.
	Rock Creek 1918	19–20 N. 78 W.	Cret. U. Jurassic	Dakota gr.[a] Sundance	Oil	35	2550 3300	Simple, asymmetric anticline. Some oil in the Frontier. Closure about 1,600 ft.
	Dutton Creek 1927	18 N. 78 W.	U. Cret.	Steele Thermopolis	Gas Oil	34	1600 4860	Small dome on the Rock River anticline. Independent closure about 500 ft.
	Rex Lake 1923	16 N. 77 W.	Cret.	Dakota gr.	Oil and gas	32	3800	Small dome with about 1,000 ft. of closure. Gas in the Shanno sandstone.
	Horne 1939	22 N. 78 W.	U. Cret.	Mowry	Gas		750	Narrow, asymmetrical anticline. Some gas in the Cloverly.
	Oil Springs 1938	23 N. 79 W.	U. Jurassic	Sundance			2231	Slightly faulted, elongated, sharp anticline. Some gas in the Frontier.
Green River Basin	Wertz 1920	26 N. 89–90 W.	L. Cret. Penn.	Cloverly Tensleep	Gas Oil	35	3650 5900	Symmetrical, slightly faulted dome with about 1,200 ft. of closure. Some gas in the Frontier and Sundance, and some oil in the Mowry.
	Eight Mile Lake (Hatfield) 1923	19–20 N. 88 W.	U. Cret.	Thermopolis	Gas		3750	Small, elliptical dome with minor faults. Some gas in the Frontier and upper Cloverly. Closure about 250 ft.
	Ferris 1919	26 N. 86–87 W.	U. Cret.	Mowry and Thermopolis	Oil	36	1750	Two elongated, sharp, symmetrical mountainward domes on a long anticline. Some oil in the Cloverly, Sundance, and Embar. Field practically depleted. Total closure of about 2,000 ft. Some 18° gravity black oil in the Chugwater.
			L. Cret. U. Jurassic	Cloverly Sundance	Gas		1850 2775	
	West Mahoney 1919	26 N. 88 W.	L. Cret. U. Jurassic Penn.	Cloverly Sundance Tensleep	Gas		2300 2700	Broad, oval, mountainward anticline with 300 ft. of closure. 44° gravity oil in the Tensleep at East Mahoney dome.
					Oil	34[b]	4300	

[a] Principal oil or gas zone.
[b] Black in color

TABLE III

Surface Types of Oil and Gas Fields in Wyoming

B. Faulted anticlines and domes

	Field and Year of Discovery	Location (Tps. & Rs.)	Principal Producing Zones: Age	Formation	Contents	Gravity A.P.I. at 60° F.	Average Depth (Feet)	Remarks
Big Horn Basin	Elk Basin 1915	57–58 N., 99–100 W.	U. Cret. L. Cret.	Frontier Cloverly	Oil Gas	40	1500 2550	Extremely faulted, rather symmetrical, oval, basinward dome with several thousand feet of closure. 30° gravity black oil discovered in late 1942 in Tensleep at depth of about 4,500 feet.
	Frannie 1928	58 N., 98 W.	Penn. Miss.	Tensleep[a] Madison	Oil	28[b] 18[b]	3000 3000+	Closure 1,000 ft. Spotted saturation in Embar.
	Big Polecat 1916	57 N., 98 W.	U. Cret.	Frontier	Gas		2400	Narrow, faulted domes with relatively small amount of closure. Big Polecat often called Danker and McMahon domes.
	Little Polecat 1922	57 N., 98–99 W.					4200	
	Byron 1918	56 N., 97 W.					2163	
			Permian-Penn.	Embar-Tensleep[a]	Oil	25[b]	5100	Extremely faulted basinward dome with 1,500 ft. of closure. Sundance yields some 32° gravity green oil at 4,200 ft.
	Garland 1906	55–56 N., 97–98 W.	U. Cret.	Frontier	Oil and gas	40	500+	Extremely faulted basinward dome with 2,600 ft. of closure. Some gas in the Morrison and Chugwater. Show of black oil at top of Sundance. Some oil in the Tensleep.
			L. Cret.	Cloverly	Gas		1750	
			Permian-Penn.	Embar-Tensleep			3500	
			Miss.	Madison[a]	Oil and gas	19[b]	4250	
	Oregon Basin 1912	50–52 N., 100–101 W.	U. Cret. L. Cret. Triassic and Permian	Frontier Cloverly Chugwater	Gas	43	900± 1500 2785±	Two large symmetrical basinward domes separated by a narrow saddle. Closure about 800 ft. in south dome and 400 ft. in north dome. Some gas in the Morrison and Sundance.
			Permian-Penn.	Embar-Tensleep[a]	Oil	22[b]	3450	
	Pitchfork 1930	43 N., 102 W.				19[b]	3475	Long, narrow, asymmetrical, mountainward dome with about 2,000 ft. of closure.
	Hamilton (Cottonwood) 1918	44 N., 98 W.	Triassic, etc. Permian Penn.	Chugwater Embar[a] Tensleep		18[b] 15[b]–27[b] 18[b]	1650 2600 2925	Asymmetrical, faulted dome with about 2,400 feet of closure.
	Red Springs 1919	43 N., 93 W.,	Miss.	Madison		11[b]	1000	Asymmetrical mountainward dome faulted at southeast end.
	Greybull 1907	52 N., 93 W.	L. Cret.	Cloverly		42	1200	Shallow, elliptical, somewhat faulted basinward dome. May be more monoclinal than domal. Some oil in a Mowry sand. Closure about 200 ft.
Wind River Basin	*Pilot Butte 1916	3 N., 1 W., W.R.M.	U. Cret.	Cody	Oil	38	1200	Asymmetrical, faulted dome. Some gas in the Cloverly and Morrison.
	Alkali Butte 1920	33–34 N., 95 W.		Thermopolis		33	3960	Narrow, elongated anticline cut by many transverse faults. Some oil in the Shannon sand and gas in Frontier, Cloverly, and Morrison.
	Muskrat 1928	33–34 N., 92 W.	U. Cret.	Frontier	Gas		4140	Surface is faulted; subsurface seems to be a series of small domes along major anticline. Embar produced some oil at a depth of 7,268 feet.
			L. Cret.	Cloverly			5400	

			L. Cret.	Cloverly			5400	depth of 7,268 feet.
Powder River Basin and vicinity	Shannon 1889	40–41 N., 79 W.	U. Cret.	Steele	Oil	24	850	Faulted segment on the north end of the Salt Creek anticline. Also classified as a monocline.
	Salt Creek Shale (1906) Sand (1908)	39–40 N., 78–79 W.	U. Cret.	Niobrara and Carlile	Oil	35–39	500	Basinward dome cut by many transverse faults. Closure 1,600 ft. Some oil in Muddy sand and in Cloverly shale. Natural water drive in the First Wall Creek sand (Frontier), basal Cloverly sand, and Tensleep sand. Extremely slow water encroachment in the Second Wall Creek sand. Madison limestone produced some oil of 22° gravity at 4,375 feet. Second Wall Creek sand is principal oil zone. In the old Shannon pool at the north end of the Salt Creek anticline oil is trapped either by faulting or by change in lithology—or by both.
				Frontier[a]	Oil and gas		930–2100	
			L. Cret.	Cloverly			2425	
			U. Jurassic	Morrison		30	2370	
				Sundance		35	2900	
			Penn.	Tensleep		27[b]	3970	
	Teapot Dome 1922	38–39 N., 78 W.	U. Cret.	Niobrara and Carlile	Oil	33–39	947–2780	Faulted dome near south end of the Salt Creek anticline. Second Wall Creek sand is principal oil zone. Some oil in Shannon sand.
				Frontier[a]	Oil and gas		2833–3110	
	Big Muddy 1916	33 N., 76 W.	U. Cret.	Steele	Oil	34	1000	Slightly faulted dome with about 500 ft. of closure.
				Frontier[a]			3000	
			L. Cret.	Cloverly			4335	
	Bison Basin 1929	27 N., 95 W.	U. Cret.	Frontier	Oil and gas	17[b]	1000	Elongated, faulted dome.
	Sheep Creek 1935	28 N., 92 W.	Permian	Embar	Oil	23[b]	2000	Very steep anticline with about 1,000 ft. of closure.
	Lost Soldier 1916	26 N., 90 W.	U. Cret.	Frontier	Oil and gas	31	550	Elliptical, faulted dome with about 3,500 ft. of closure. Some oil in the Mowry and in the Morrison. Cretaceous and Pennsylvanian oil is brownish green and Sundance oil is brownish black.
			L. Cret.	Cloverly[a]			1550	
			U. Jurassic	Sundance[a]			1900	
			Penn.	Tensleep[a]		35	4250	
	Bunker Hill 1937	27 N., 89 W.	U. Cret.	Steele	Gas		1700	Oval-shaped, faulted dome on mountainward side of Wertz dome. Closure is 800 ft.
	North Baxter Basin 1926	19–20 N. 103–104 W.	U. Cret.	Dakota (?)			3100	Rather low, faulted dome 1,200 ft. lower structurally than South Baxter Basin. Gas also in a Morrison sand.
			U. Jurassic	Sundance			3500	
	Middle Baxter Basin 1938	18 N., 103–104 W.	U. Cret.	Frontier			1700	Elongated, faulted domes along Rock Springs anticline with North Baxter Basin. Dakota (?) gas is sour.
				Dakota (?)			2483	
	South Baxter Basin 1922	16–18 N., 103–104 W.	U. Cret.	Frontier			2120	
				Dakota (?)			2860	
	Labarge 1924	26–27 N., 113 W.	Eocene		Oil and gas	17–45	900	Low dome on an anticline lying 2 miles east of the Darby overthrust. Some 45° gravity oil at North Labarge.
	Dry Piney 1918	28 N., 113–114 W.	U. Cret.	Hilliard		40	750	Low, narrow anticline.
C. Structural Noses.								
	G. P. 1920	25 N., 86 W.	U. Cret.	Niobrara	Oil	37	3000	Accumulation probably caused by sand lensing, porosity variation, etc.

TABLE III (*Cont.*)

	Field and Year of Discovery	Location (Tps. & Rs.)	Principal Producing Zones: Age	Formation	Contents	Gravity A.P.I. at 60° F.	Average Depth (Feet)	Remarks
D. Monoclines and structural terraces.								
Powder River Basin	Douglas 1894	32 N., 73 W.	Oligocene	White River	Oil	36	400	Accumulation in coarse, lenticular sands in lower part of overlapping White River formation.
	Shawnee 1936	32 N., 69 W.				25	675	
	Shannon 1889	40–41 N., 79 W.	U. Cret.	Steele		24	850	Faulted monoclinal segment on Salt Creek anticline.
	Pedro 1924 (?)	45–46 N., 62–63 W.		Graneros		30	300	Oil accumulation in shale pockets.
	Osage 1919	45–47 N., 63–64 W.				40	100–3323	Oil accumulation caused by lensing of the Newcastle sandstone on structural terraces on a gentle monocline. Some shale oil.
	Thornton 1915	48–49 N., 66 W.		Carlile		40	700	Terraces on a gentle monocline.
	Wakeman 1919	49 N., 66 W.				39	850	
	Moorcroft 1887	51–52 N., 67 W.		Graneros		22[b]	725	Oil has accumulated in lenses of sandstone in sandy shale and carbonaceous shale.
	Rocky Ford 1909	52 N., 62 W.	Penn.	Minnelusa		15[b]	175+	In top of Minnelusa on synclinal axis. Field abandoned.
	Dewey 1936	41 N., 60 W.				31[b]	2300	Gentle, slightly faulted monocline. Some Sundance oil.
	Spring Valley 1900	15 N., 118 W.	U. Cret.	Aspen[a] Bear River		40	500–2000 900	Accumulation is in a sand lense on a monocline sealed by overlapping Tertiary strata.

* For new data acquired since table was compiled see ADDENDA, pages 475 and 478.
[a] Principal oil or gas-producing zone.
[b] Black in color.

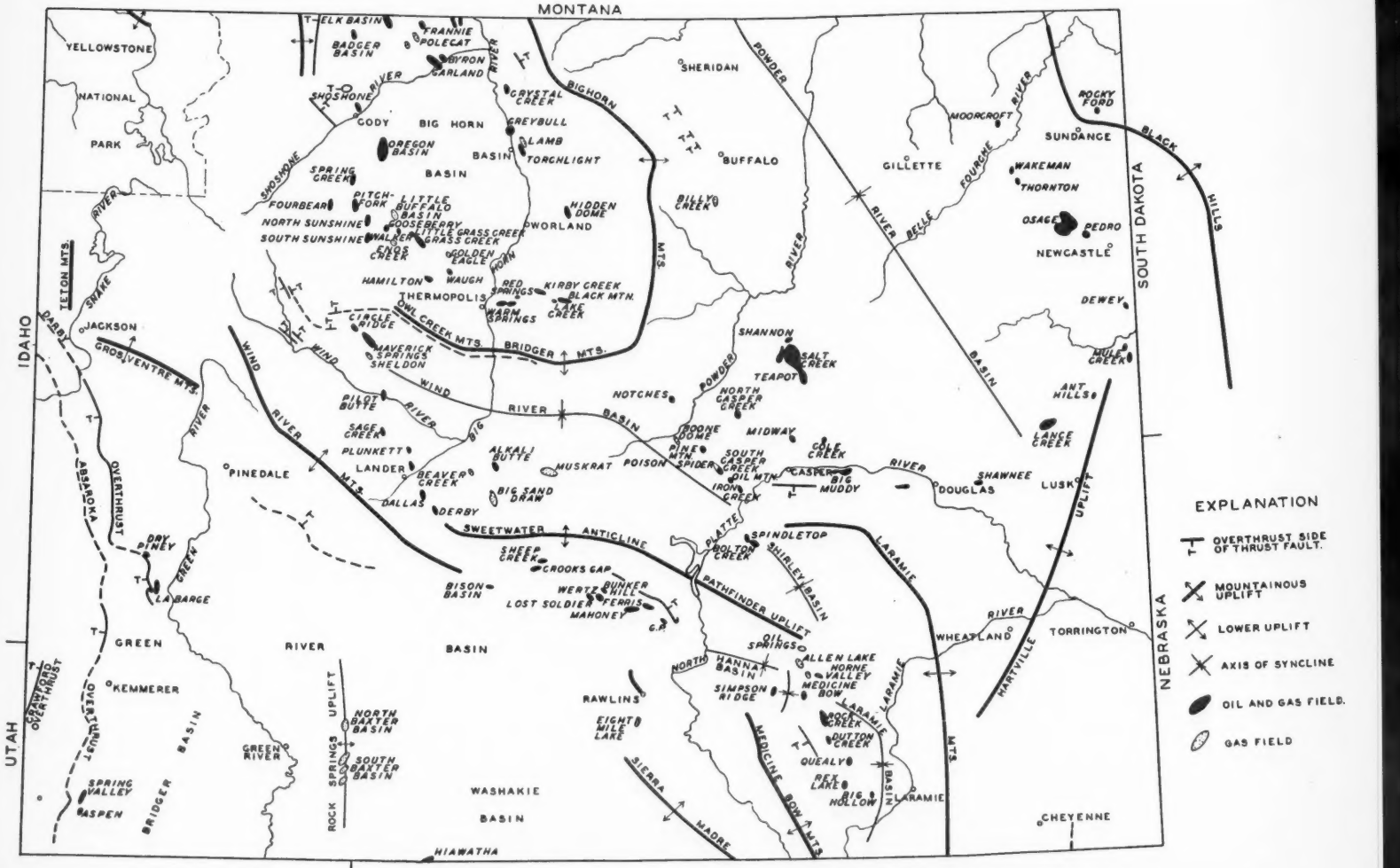


FIG. 5 — OIL AND GAS FIELDS AND MAIN STRUCTURAL FEATURES OF WYOMING.

7), Grass Creek (2,400 feet), and others; there are narrow, asymmetrical anticlines with small amounts of structural closure, such as Kirby Creek; and there are overturned anticlines, such as Lander (Hudson). Nine of the 21 relatively

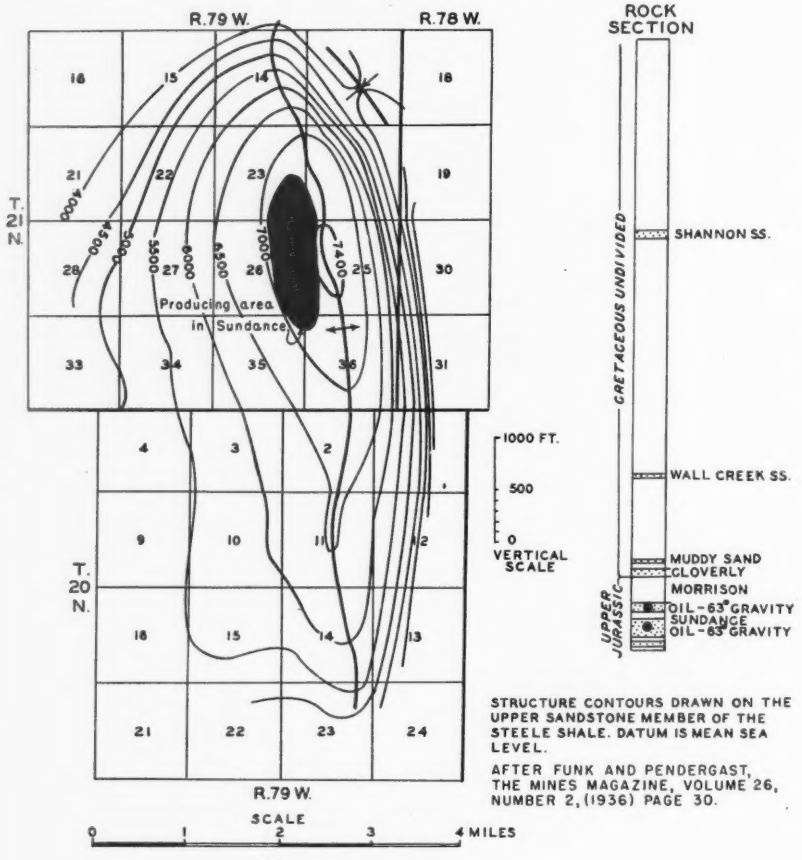


FIG. 6

MEDICINE BOW ANTICLINE, CARBON COUNTY, WYOMING.

large and important producing oil and gas fields in Wyoming are unfaulted or only slightly faulted anticlines and domes.

COLORADO[53]

Twenty of the 28 oil and gas fields in Colorado are on unfaulted or slightly

[53] See also:
Clark F. Barb, "The Oil and Gas Industry of Colorado," *Colorado School Mines Quar.*, Vol. 37, No.2 (1942).

faulted anticlines and domes. Nine of the aforementioned 20 fields are on very low anticlines that produce relatively small amounts of oil or gas, 8 fields are on rather long, sharp, symmetrical anticlines, and 3 fields are on large, asymmetrical domes—Moffat, Wilson Creek (Fig. 10), and Rangely with the respective surface

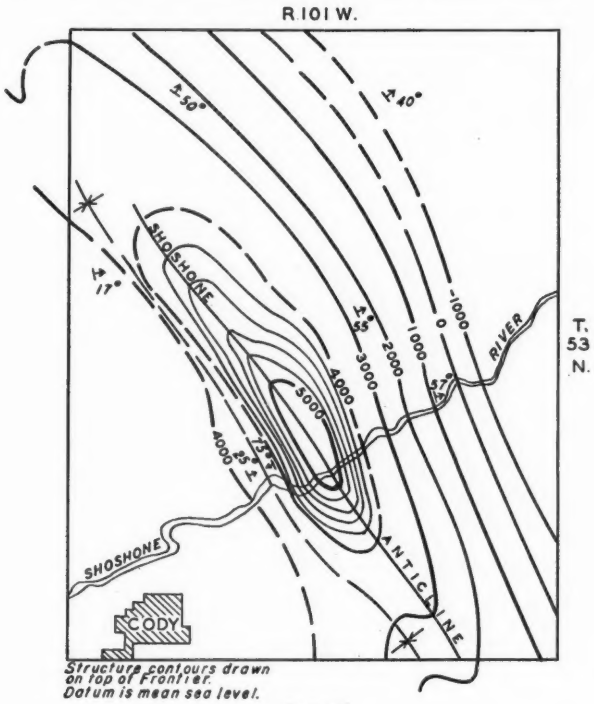


FIG. 7

SHOSHONE ANTICLINE, PARK COUNTY, WYOMING.

AFTER W.G. PIERCE, U.S GEOLOGICAL SURVEY (1939)

SCALE 0 1 MILE

structural closures of about 900 feet, 1,000 feet and 2,000 feet. Four of the seven relatively important oil and gas fields in the state are on unfaulted or slightly faulted anticlines and domes.

NORTHERN NEW MEXICO[54]

Five of the 13 oil and gas fields in northern New Mexico are on unfaulted or slightly faulted anticlines and domes in the San Juan Basin. The Hospah, Table

[54] See also:

Dean E. Winchester, "The Oil and Gas Resources of New Mexico," *New Mexico School Mines and State Bur. Mines and Min. Res. Bull. 9* (1933).

———, "Natural Gas in Colorado, Northern New Mexico and Utah," *Geology of Natural Gas* (Amer. Assoc. Petrol. Geol., 1935), pp. 363–84.

Mesa, and Rattlesnake fields, are on low domes with respective structural closures of about 100, 150, and 100 feet; the Stony Butte field is on a long, narrow anticline; and Hogback field is an asymmetrical dome with about 300 feet of structural closure. Two of the four relatively important oil and gas fields in the northern part of the state are on unfaulted or slightly faulted domes.

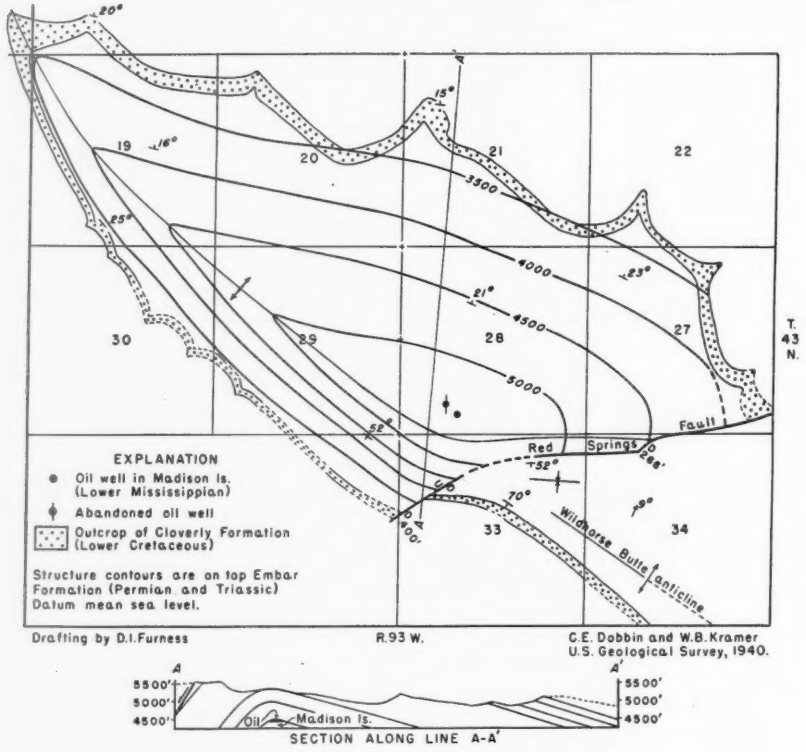


Fig.8-RED SPRINGS ANTICLINE, HOT SPRINGS COUNTY, WYOMING

UTAH

Six of the 10 fields in Utah—all being gas fields, except the small Virgin field—are on unfaulted anticlines and domes, but only one—Clay Basin—is of present relative economic importance. Two of the fields (Clay Basin and Cisco) are on rather symmetrical domes; the Last Chance field is on a broad, asymmetrical dome; the Woodside field is a sharp, asymmetric dome with 800 feet of closure; and the Harley field is on a low dome with 90 feet of structural closure.

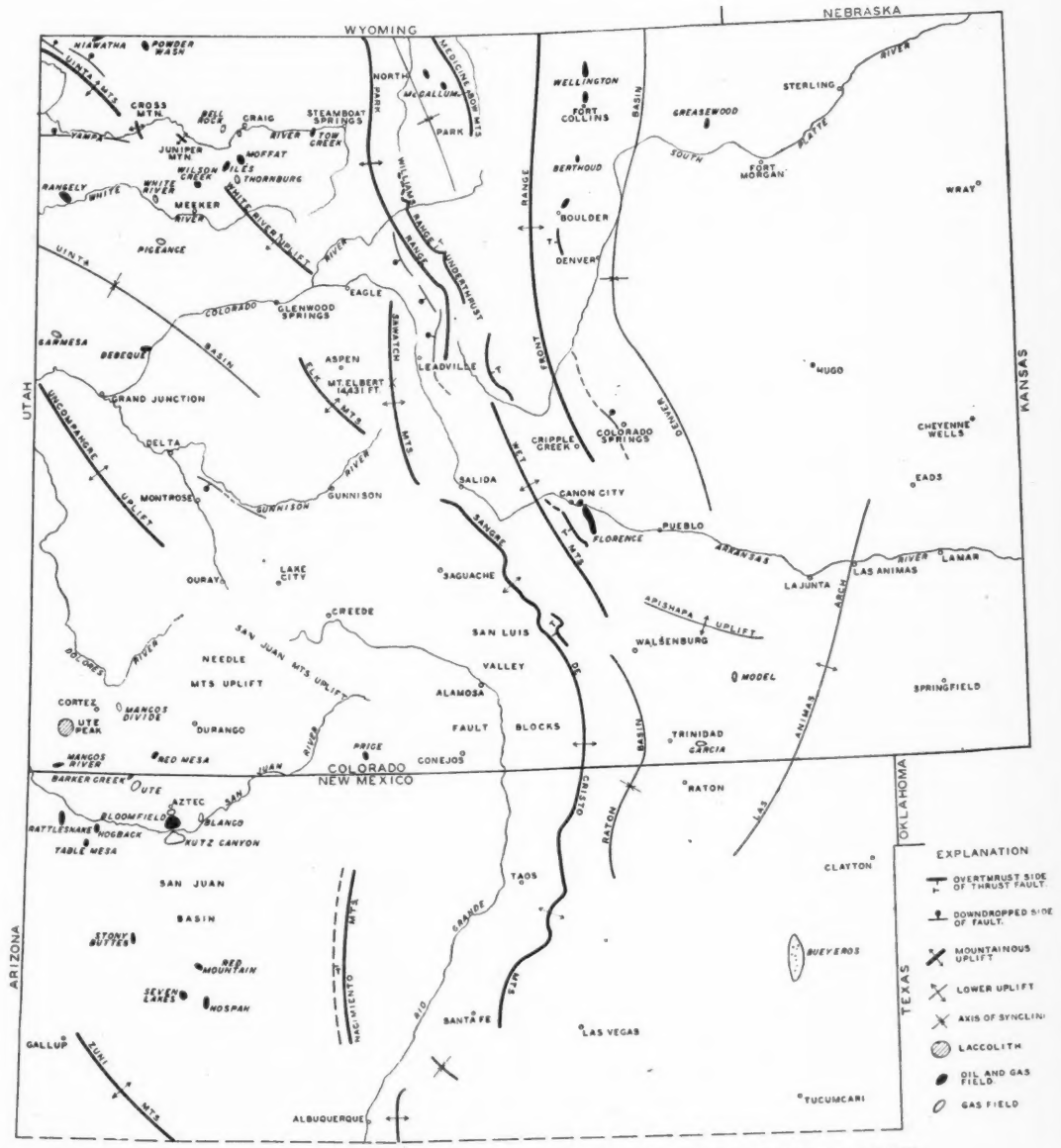


FIG 9—OIL AND GAS FIELDS AND MAIN STRUCTURAL FEATURES OF COLORADO AND NORTHERN NEW MEXICO.

TABLE IV

Surface Types of Oil and Gas Fields in Colorado

A. Anticlines and domes whose productive areas are either not faulted or only slightly faulted.

Field and Year of Discovery	Location (Tps. & Rs.)	Principal Producing Zones						Remarks
		Age	Group or Formation	Member	Contents	Gravity A.P.I. at 60° F.	Depth (Feet)	
Greasewood 1930	6 N., 61 W.	Cretaceous	Dakota group		Oil and gas	41	6650	A very low anticline with possibly some surface closure. One normal fault, low folding, and sand lensing control accumulation.
Wellington 1923	9–10 N., 68 W.			Muddy sand		37	4300	Closed domes on the Wellington anticline. Subsurface closure at Wellington is about 1100 ft. and at Fort Collins about 800 ft.
Fort Collins 1924	8 N., 68 W.			Middle ss.		35		
Berthoud 1927	4 N., 69 W.		Pierre et al Dakota gr.	Shale		38	2400 to 3800±	An unfaulted anticline with about 200 ft. of closure. Shale oil is in Benton, Niobrara, and Pierre.
				Muddy sd.[a]				
Wray 1920 (?)	2 S., 43 W.		Carlile		Gas		1600	A low dome. Gas reservoir depleted.
Model Dome 1929	29–30 S., 60 W.	Jurassic (?)	?				1000	Small, asymmetrical dome on the Apishapa uplift. Helium content of gas is 7.2 per cent. Closure is about 250 ft.
Hiawatha 1926	12 N., 100–101 W.	Eocene	Wasatch		Oil and gas	38	1600–2800	Two quaquaversal domes producing from irregular and lenticular fluviatile and lacustrine porous sands. Independent closure at Hiawatha is 235 ft.; at West Hiawatha 57 ft.; and at Powder Wash 90 ft.
Powder Wash 1931	12 N., 97–98 W.						2152–5032	
Tow Creek 1924	6 N., 86 W.	Upper Cretaceous	Mancos	Shale	Oil	37	2600	Long, sharp, asymmetrical anticline. Accumulation probably caused by fracturing of shale by folding. Best wells are where steep dip begins.
Rangely 1902	2 N., 102 W.					41	372–1000	Large, asymmetrical dome with a closure of 2000 ft. Mancos production is where gentle dip changes to steep dip.
			Dakota (?)		Gas		3000	
		Penn.	Weber		Oil	33	5704–6300	
Thornburg 1924	3 N., 91 W.	Upper Cret. Upper Jur.	Dakota (?) Sundance		Gas	38–41	2000 2550	Slightly asymmetrical and almost unfaulted dome. Some oil in Frontier in 1 well and in Sundance in another.
Moffat (Hamilton) 1924	4–5 N., 91 W.	Upper Cret.	Dakota (?)		Oil		3877	Pronounced asymmetrical dome with a closure of about 900 ft. Some minor faults at surface.
		Upper Jur.	Morrison Sundance				4427 4538	
White River 1890	2 N., 96–97 W.	Eocene	Wasatch		Gas		600–900	Dome with a closure of 400 ft. A few minor faults and a little oil.
Piceance 1930	2 S., 96 W.		Green River and Wasatch	Sdy. zones at and near contact			2800	Elongated unfaulted dome with 250 feet of closure.

Debeque 1902	8 S., 97–98 W.	Upper Cret.	Mesaverde		Oil and gas	38	614	Slight closure on a low anticline which has trapped oil in lenticular sands. No wells in area of closure.
Garmesa 1925	8 S., 102 W.	Upper Cret.	Dakota (?)		Gas		2860	Long, narrow, strongly asymmetric dome with about 250 feet of surface closure. Gas contains 20–61 per cent of CO_2.
		Upper Jur. Jurassic (?)	Morrison Kayenta and Wingate				3320 3755	
Wilson Creek 1938	2–3 N., 93–94 W.	Upper Jur.	Morrison Sundance		Oil	48	6600 6700	Large dome on the Danforth Hills anticline. One strike fault on steep southwest flank. Closure 1000 ft.
Bell Rock 1930	6 N., 92 W.	Upper Cret.	Mesaverde group	Iles	Gas		2845	Dome at north end of Williams Fork anticline. Several small faults at north end.
Price 1935	33 N., 1–2, E. N.M. Mer.	Upper Cret.	Dakota (?)		Oil	32	1300	A narrow anticline almost surrounded by extrusive rocks.
Red Mesa 1924	33 N., 12 W. N. M. Mer.		Mesaverde Dakota (?)		Gas Oil	42	700 3500	Narrow, elongated dome with about 20 feet of closure. Abandoned.

B. Faulted anticlines and domes.

Craig (Breeze) 1932	6 N., 91 W.	Upper Cret.	Mesaverde gr.	Iles	Gas		2733	Elongated anticline with north side dropped about 200 ft. by strike fault.
			Mancos	Morapos sd.			3419	
Iles 1925	4 N., 92 W.			Mowry shale	Oil	36	2600	Dome with about 900 ft. of closure on the main axis of the Axial Basin anticline. Non-producing area cut by many faults, the largest having a throw of 1000 ft. Some oil in the Dakota.
		Upper Jur.	Morrison Sundance	Basal sand		32	3200	
					Oil and gas	32	3400	
McCallum 1926	9–10 N., 78–79 W.	Upper Cret.	Dakota (?)		Gas and oil	48	5000	Two sharp, offsetting anticlines on east edge of North Park synclinal basin. Gas contains 92 per cent of CO_2. North McCallum has total structural closure of about 1300 feet and south McCallum more than 1500 feet.

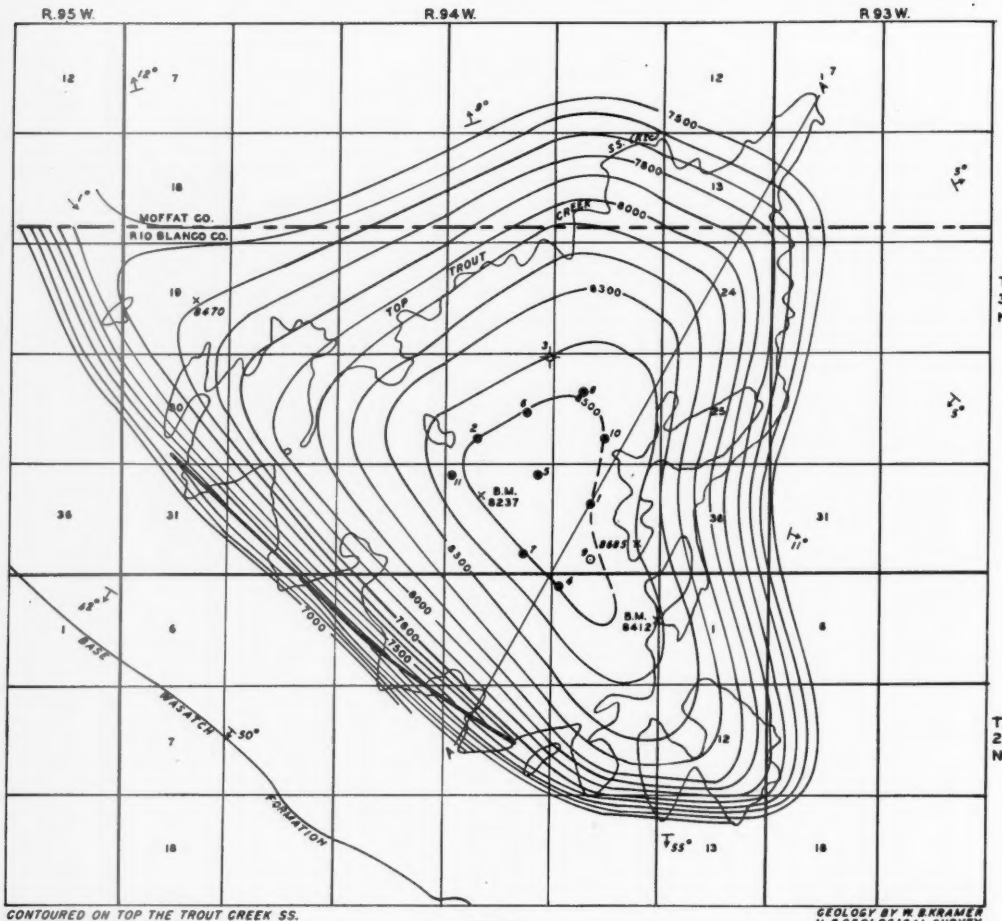
C. Structural Noses.

Canyon City 1926	18–19 S., 70 W.	Upper Cret.	Pierre	Fractured zones	Oil	31	910–2154	Oil occurs in shale fissures along an anticlinal nose.

D. Monoclines and structural terraces.

Boulder 1901	1– 2 N., 70–71 W.	Upper Cret.	Pierre	Sands and sandy sh.	Oil	41	1000–2800	Accumulation on a terraced monocline where there is a decided arresting of a general east dip. Produced gas once.
Florence 1876	19–20 S., 69 W.					31	1100–3600	On the east flank of a complicated synclinal basin. Oil is in joints and fissures in shale. No faults in producing area.
Garcia 1898 (?)	34 S., 62 W.		Pierre Apishapa		Gas		700–1700	Accumulation in sand lenses on the southwest flank of a low-plunging anticline. Closure less than 150 ft.
Mancos Creek 1927	32 N., 18 W., N.M. Mer.		Mancos		Oil	34	300	Small terrace on a monocline. Production was from shale. Field abandoned.

[a] Principal oil or gas zone.
[b] No black oil produced in Colorado.
[c] No oil production from limestone in Colorado.



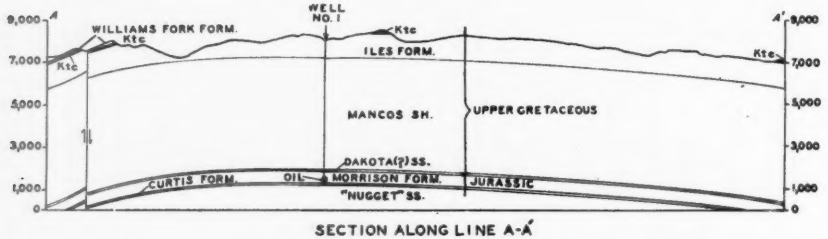
CONTOURED ON TOP THE TROUT CREEK SS. DATUM, MEAN SEA LEVEL

GEOLOGY BY W. B. KRAMER U. S. GEOLOGICAL SURVEY, 1938.

FIG. 10

GEOLOGIC MAP OF THE WILSON CREEK DOME, RIO BLANCO AND MOFFAT COUNTIES, COLORADO.

SCALE 0 1 MILE



SECTION ALONG LINE A-A'

FAULTED ANTICLINES AND DOMES

Only 46 fields, or 26 per cent, of the 180 oil and gas fields in the Rocky Mountain region are faulted to any extent at the surface, and only 17 of these are of relative importance. In retrospect, these figures are of interest, for it was long believed that unfaulted or slightly faulted structures are likely to be either gas-bearing or barren.

Practically all faulting in known fields in the region is of the normal type, classed by Irwin[55] as epi-anticlinal, occurring in parallel or radial systems on the crests and flanks of anticlines, and as fault closures. The probable exceptions to this classification are the faulted gas-bearing structures in the Bearpaw Mountains shallow thrust-fault zone, north-central Montana. That the steeply dipping epi-anticlinal normal faults occurring in exposed and drilled sections of relatively thick Upper Cretaceous shale and relatively thin sandstone beds resulted from relaxational movements in highly compressible shale subsequent to folding seems probable, and particularly so as they die out with depth as competent beds are reached. It is unfortunate, however, that even in most of the closely drilled fields sufficiently accurate surface and subsurface data are lacking to delimit a correct fault pattern, particularly the relationship between surface and subsurface faults.

Among the many fields in the Rocky Mountain region that display epi-anticlinal faulting well are Cat Creek[56] and Dry Creek, Montana; Elk Basin,[57] Garland (Fig. 12), Hamilton,[58] Salt Creek,[59] and Lost Soldier,[60] Wyoming.

MONTANA

Ten of the 27 oil and gas fields in Montana are faulted anticlines and domes and fault blocks. Six of these 10 are on small, faulted anticlines and fault blocks

[55] J. S. Irwin, "Faulting in the Rocky Mountain Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 2 (1926), pp. 105–29.

[56] Frank Reeves, "Geology of the Cat Creek and Devils Basin Oil Fields and Adjacent Areas in Montana," *U. S. Geol. Survey Bull. 786* (1927), pp. 39–95.

[57] John G. Bartram, "Elk Basin Oil and Gas Field, Park County, Wyoming, and Carbon County, Montana," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 577–88.

Edward L. Estabrook, "Faulting in Wyoming Oil Fields," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7, No. 2 (1923), pp. 95–102.

[58] W. B. Kramer, "Geologic Map and Section of Hamilton Dome and Wagonhound Anticline, Hot Springs County, Wyoming," *U. S. Geol. Survey* (1942).

[59] Elfred Beck, "Salt Creek Oil Field, Natrona County, Wyoming," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 589–603.

W. T. Thom, Jr., and Edmund M. Spieker, "The Significance of Geologic Conditions in Naval Petroleum Reserve No. 3, Wyoming," *U. S. Geol. Survey Prof. Paper 163* (1931), pp. 1–38.

C. H. Wegemann, "The Salt Creek Oil Field, Wyoming," *ibid., Bull. 670* (1917).

[60] A. E. Fath and G. F. Moulton, "Oil and Gas Fields of the Lost Soldier-Ferris District, Wyoming," *ibid., Bull. 756* (1924).

J. S. Irwin, "Oil and Gas Fields of Lost Soldier District, Wyoming," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol. (1929), pp. 636–66.

E. W. Krampert, "The Oil Fields of the Rawlins-Lost Soldier District, Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7, No. 2 (1923), pp. 131–46.

Allen W. Tillotson, "Gas Fields of Lost Soldier District, Carbon and Sweetwater Counties, Wyoming," *Geology of Natural Gas* (Amer. Assoc. Petrol. Geol., 1935), pp. 305–22.

TABLE V

Surface Types of Oil and Gas Fields in Northern New Mexico

San Juan Basin

A. Anticlines and domes whose productive areas are either not faulted or only slightly faulted.

Field	Location (Tps. & Rgs.)	Principal Producing Zones						Remarks
		Age	Formation	Member	Contents	Gravity A.P.I. at 60° F.	Depth (Feet)	
Hospah 1927	17–18 N., 8– 9 W.	Upper Cretaceous	Mesaverde	Hosta sand	Oil	30	1573	Dome with about 100 feet of closure. Producing area not faulted.
Stony Butte 1928	22 N., 14 W.					31[b]	814	Long, narrow uplift with three high points. Has numerous faults with 50-ft. or less throws.
Hogback 1922	29 N., 16 W.		Dakota (?)			65	725	Very asymmetrical dome with about 300 feet of closure. Lensing of sands probably important factor in oil accumulation.
Table Mesa 1925	27 N., 17 W.					62	1315	Symmetrical dome cut by one fault with a throw of about 50 feet. Closure about 150 feet.
Rattlesnake 1924	29 N., 19 W.					76–63	730	Elongated almost symmetrical dome. Faulting minor. Dakota (?) production due to a combination of sand lensing and local doming.
		Pennsylvanian	Hermosa			42	6700	Dakota (?) consists of 4 erratic sands separated by sandy shale. Closure about 100 feet.
B. Faulted anticlines and domes.								
Red Mtn. 1936	20 N., 9 W.	Upper Cretaceous	Mesaverde		Oil	43	440	Small, faulted structure.
Barker Creek 1925	32 N., 14 W.		Dakota (?)		Gas		3123	Slightly asymmetrical elongated dome with a closure of at least 300 feet.
Ute Dome 1921	31–32 N., 14 W.						2350	Asymmetrical dome cut by many faults.
Bueyeros 1931	18–21 N., 30–31 E.	Upper (?) Triassic	Dockum group	Santa Rosa (?) ss.			700	Low faulted domes. Gas contains 98 per cent CO_2.
D. Monoclines.								
Seven Lakes 1911	18 N., 10 W.	Upper Cretaceous	Mesaverde		Oil	38	350	Accumulation in lenticular sands in a gentle northeast-dipping monocline.
Blanco 1926	29–30 N., 9 W.		Pic. Cliffs Mesaverde		Gas		2220 4152	Gentle monocline. Some oil in the Farmington sandstone.
Aztec-Bloomfield 1920	28–30 N., 11 W.		Kirtland	Farmington ss.	Oil and gas	55	700–1500	Monocline dipping 25 ft. per mile northeast. Oil is in shale-sealed sand lenses.
Kutz Canyon 1927	28–29 N., 10–11 W.		Pictured Cliffs		Gas		1850	Very gentle northeast dip. Accumulation may be caused by lensing of porous sand members.

[b] Black in color.

TABLE VI

Surface Types of Oil and Gas Fields in Utah

A. Anticlines and domes whose productive areas are either not faulted or only slightly faulted.

Field	Location (Tps. & Rgs.)	Principal Producing Zones						Remarks
		Age	Formation	Member	Contents	Gravity A.P.I. at 60° F.	Depth (Feet)	
Clay Basin 1927	3 N., 24 E.	Upper Cretaceous	Frontier		Gas		5400	Symmetrical dome lying just north of the Uinta fault. Closure about 450 feet.
			Dakota (?)				5724	
Cisco 1924	20 S., 21–22 E.						1950	Symmetrical unfaulted dome with about 250 feet of closure.
		U. Jurassic	Morrison				2170	
Harley 1926	19 S., 25 E.						564	Small, asymmetrical, unfaulted dome with 90 feet of closure. Gas contains 7.16 per cent of helium.
			Entrada				945	
Last Chance 1934	25–27 S., 6– 7 E.	L. Triassic	Moenkopi				2530–2771	Broad, asymmetrical dome. Closure about 700 feet.
Woodside 1924	19 S., 13 E.	Permian	Coconino (?)				3120	Sharp, asymmetric dome with 800 feet of closure. Gas contains 1.31 per cent of helium.
Boundary Butte 1924	43 S., 22–23 E.	Triassic Penn.	Shinarump Hermosa		Oil Gas		1565 5100	Long, asymmetrical anticline with about 500 feet of closure.

B. Faulted anticlines and domes.

Ashley Valley 1925	5 S., 22 E.	U. Jurassic	Morrison		Gas		1663	Small, asymmetrical, faulted dome. Practically depleted.
Farnham 1924	15 S., 11 E.	Permian	Coconino				3086	Long, narrow faulted anticline with about 500 feet of closure. Gas contains 98.3 per cent CO_2.

D. Monoclines.

San Juan 1908	42 S., 19 E., and vicinity	Permian Penn.	Rico Hermosa		Oil	39	250±	Production from sands on west limb of gentle Mexican Hat syncline.
Virgin 1907	42 S., 11–12 W.	L. Triassic Permian	Moenkopi Kaibab	Base Top		30	500–800	Gentle, east-dipping monocline just east of Hurricane fault.

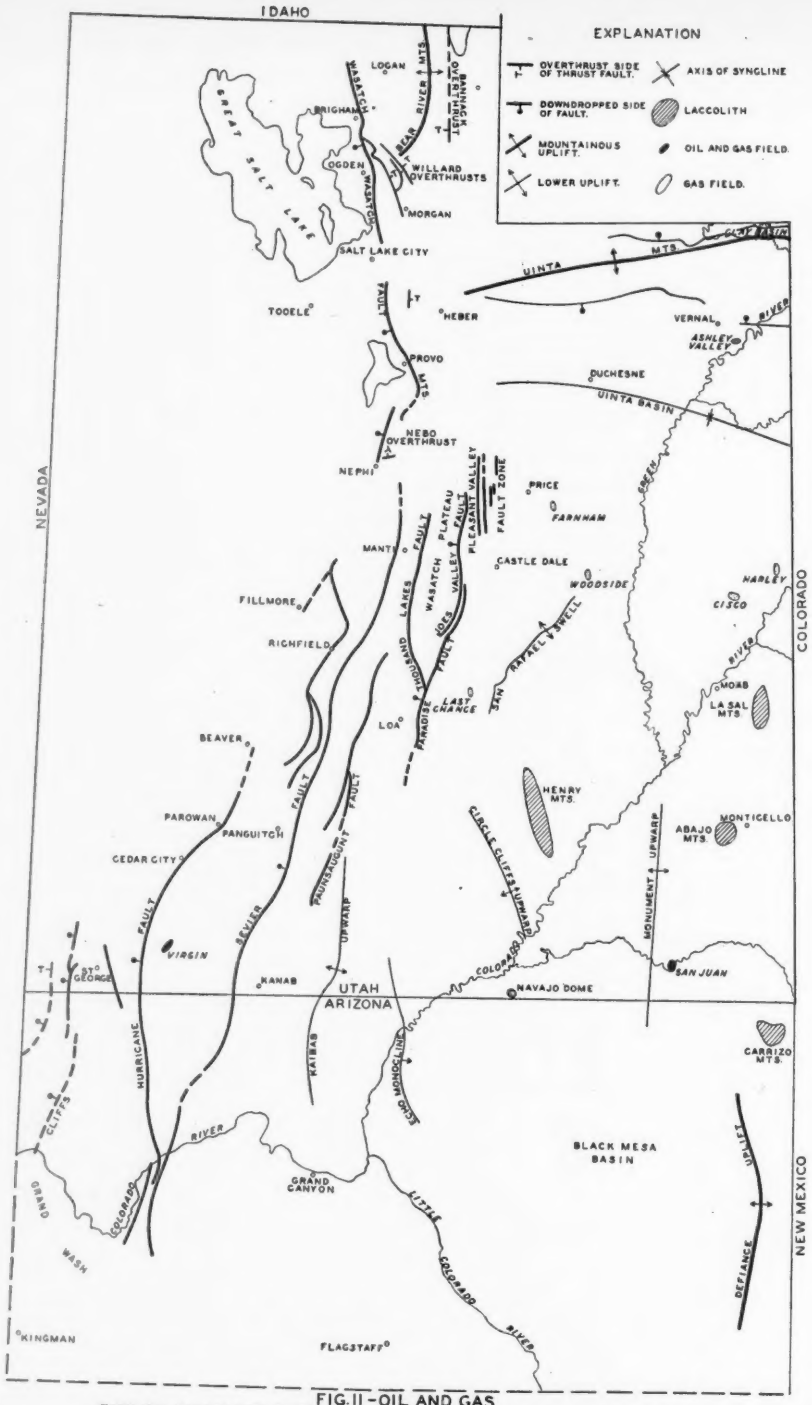


FIG. II - OIL AND GAS FIELDS AND MAIN STRUCTURAL FEATURES OF EASTERN UTAH AND NORTHERN ARIZONA.

in the Bearpaw Mountains shallow thrust-fault zone in the north-central part of the state, two—Armells (Cone Butte) and Cat Creek—are in the Big Snowy anticlinorium, Mosser is at the north end of the Pryor Mountains uplift, and Dry Creek is between that uplift and the Beartooth uplift. The only relatively important fields in this classification in the state are the Bowes gas field, the Cat Creek oil field, and the Dry Creek[61] oil and gas field, the first-named having a closure of about 200 feet, the second being two faulted domes on an elongate anticline, and the third being an extremely faulted dome with about 1,500 feet of closure.

WYOMING

Twenty-seven of Wyoming's 102 oil and gas fields are on faulted anticlines and domes, which have highly varying types of structural definition. Two of the fields—Big Muddy and Greybull[62]—seemingly are rather lightly faulted at the surface; 14 of the fields are fairly symmetrical, rather oval, and extremely faulted domes having large structural closure, for example, Elk Basin (3,000± feet), Garland (2,600± feet), and Salt Creek (1,600 feet). Ten of the fields in this classification are rather elongated, narrow, and unsymmetrical anticlines, such as Pitchfork,[63] and Alkali Butte; and one field—Labarge—may be a complexly faulted structure resembling an anticline. Eleven of the 21 relatively important oil and gas fields in the state are in this classification, others being Lost Soldier, the Baxter Basin[64] gas fields, Frannie,[65] Byron,[65] Oregon Basin, Hamilton, and Muskrat.

COLORADO

In Colorado, only 3 of the 28 oil and gas fields are on faulted anticlines and domes, and only one field—Iles—is of relative economic importance now. Iles dome has about 900 feet of structural closure and its non-productive area is cut by many faults, one of which has a throw of about 1,000 feet. Other oil and gas fields falling in this classification are North and South McCallum[66] and Craig (Breeze).

[61] W. B. Emery, "Gas Fields of Big Horn Basin Structural Province, Wyoming and Montana," *Geology of Natural Gas* (Amer. Assoc. Petrol. Geol., 1935), pp. 277–95.

[62] D. F. Hewett and C. T. Lupton, "Anticlines in the Southern Part of the Big Horn Basin, Wyoming," *U. S. Geol. Survey Bull. 656* (1917), pp. 58–67.

[63] W. G. Pierce and D. A. Andrews, "Geology and Oil and Coal Resources of the Region South of Cody, Park County, Wyoming," *U. S. Geol. Survey Bull. 921* (1941), p. 145.

[64] W. B. Kramer and G. G. Frazier, "Geologic Map and Sections of the Northern Part of the Baxter Basin Gas Field, Sweetwater County, Wyoming," *U. S. Geol. Survey* (1940).
W. T. Nightingale, "Geology of Baxter Basin Gas Fields, Sweetwater County, Wyoming," *Geology of Natural Gas* (Amer. Assoc. Petrol. Geol., 1935), pp. 323–39.
J. D. Sears, "Geology of the Baxter Basin Gas Field, Sweetwater County, Wyoming," *U. S. Geol. Survey Bull. 781* (1926), pp. 13–27.

[65] D. A. Andrews *et al.*, "Preliminary Map Showing Geologic Structure of Byron-Frannie Area, Big Horn and Park Counties, Wyoming," *U. S. Geol. Survey* (1938).

[66] J. C. Miller, "Geology of the North and South McCallum Anticlines, Jackson County, Colorado, with Special Reference to Petroleum and Carbon Dioxide," *U. S. Geol. Survey Cir. 5* (1934).

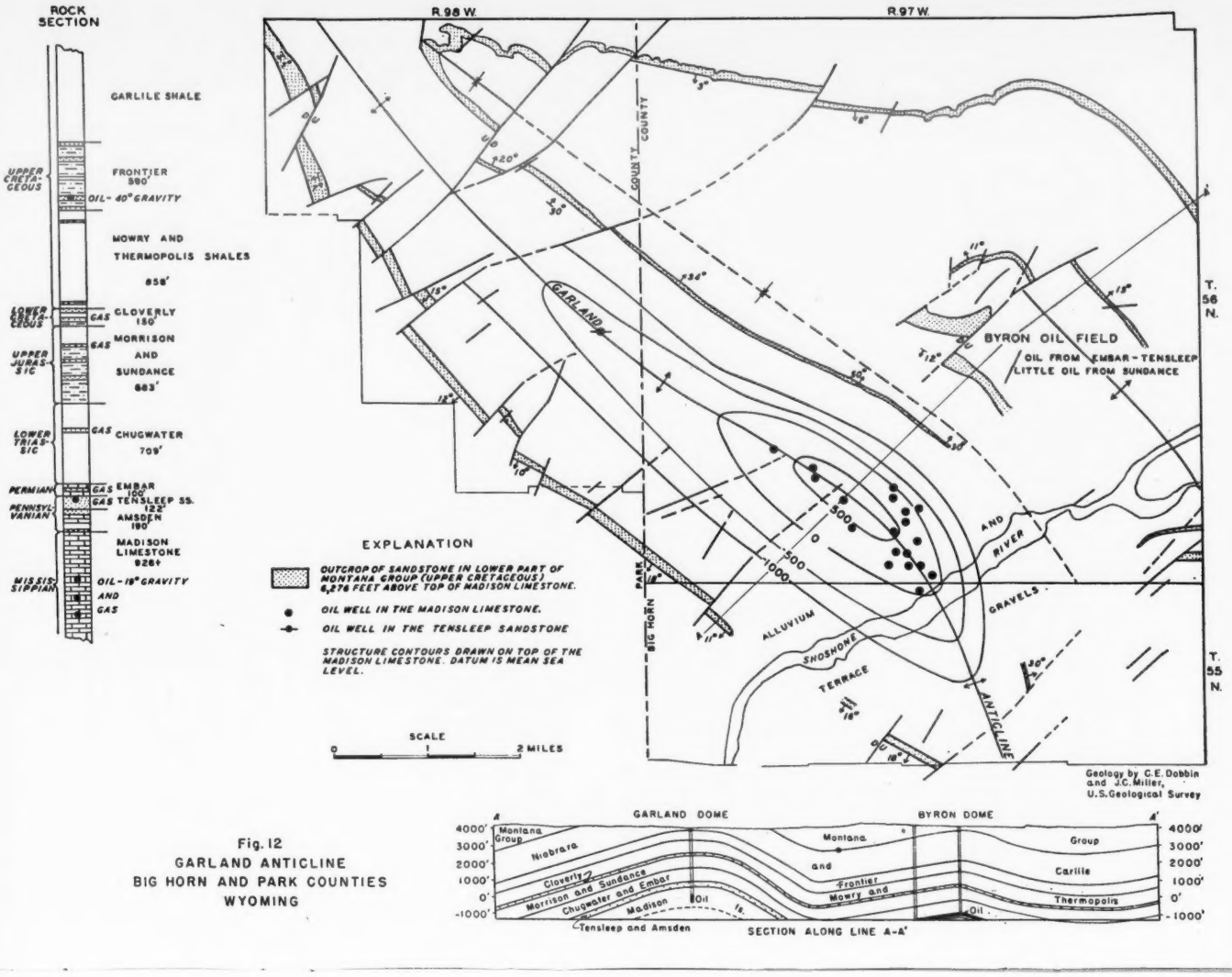


Fig. 12
GARLAND ANTICLINE
BIG HORN AND PARK COUNTIES
WYOMING

NORTHERN NEW MEXICO[67]

In northern New Mexico, 4 of the known 13 oil and gas fields are on faulted anticlines and domes, one—the small Red Mountain field—being an oil field and the others being gas fields, namely, Ute dome, Barker Creek, and the Bueyeros area. Ute and Barker Creek domes are considerably faulted, whereas the Red Mountain area and the low domes in the Bueyeros area are rather lightly faulted. Ute dome is relatively important because of its supply of hydrocarbon natural gas and the Bueyeros area for its rich carbon-dioxide natural gases.[68]

UTAH

The almost depleted Ashley Valley gas field and Farnham gas dome are the only fields in Utah whose producing areas are rather severely faulted. The Ashley Valley field is on a small, asymmetrical faulted dome and Farnham dome[69] is a long, narrow, faulted anticline yielding natural gas containing 98.0 per cent carbon dioxide.

MONOCLINES AND STRUCTURAL TERRACES

MONTANA

In Montana, oil and gas fields occur on the Cut Bank[70] monocline and on the Pondera and Hardin structural terraces, the first two named being among the 8 relatively important fields of the state. The main producing sand in the Cut Bank district—the Cut Bank sand—feathers out updip forming a stratigraphic trap. The average westward regional dip is about 50 feet per mile.

The Pondera field is a structural terrace on the steep northwest flank of a low, elongate fold, oil and gas accumulation resulting from a combination of terrace structure and variations in porosity.

The small Hardin gas field is essentially a terrace on a plunging anticline trending northeast off the Big Horn uplift.

WYOMING

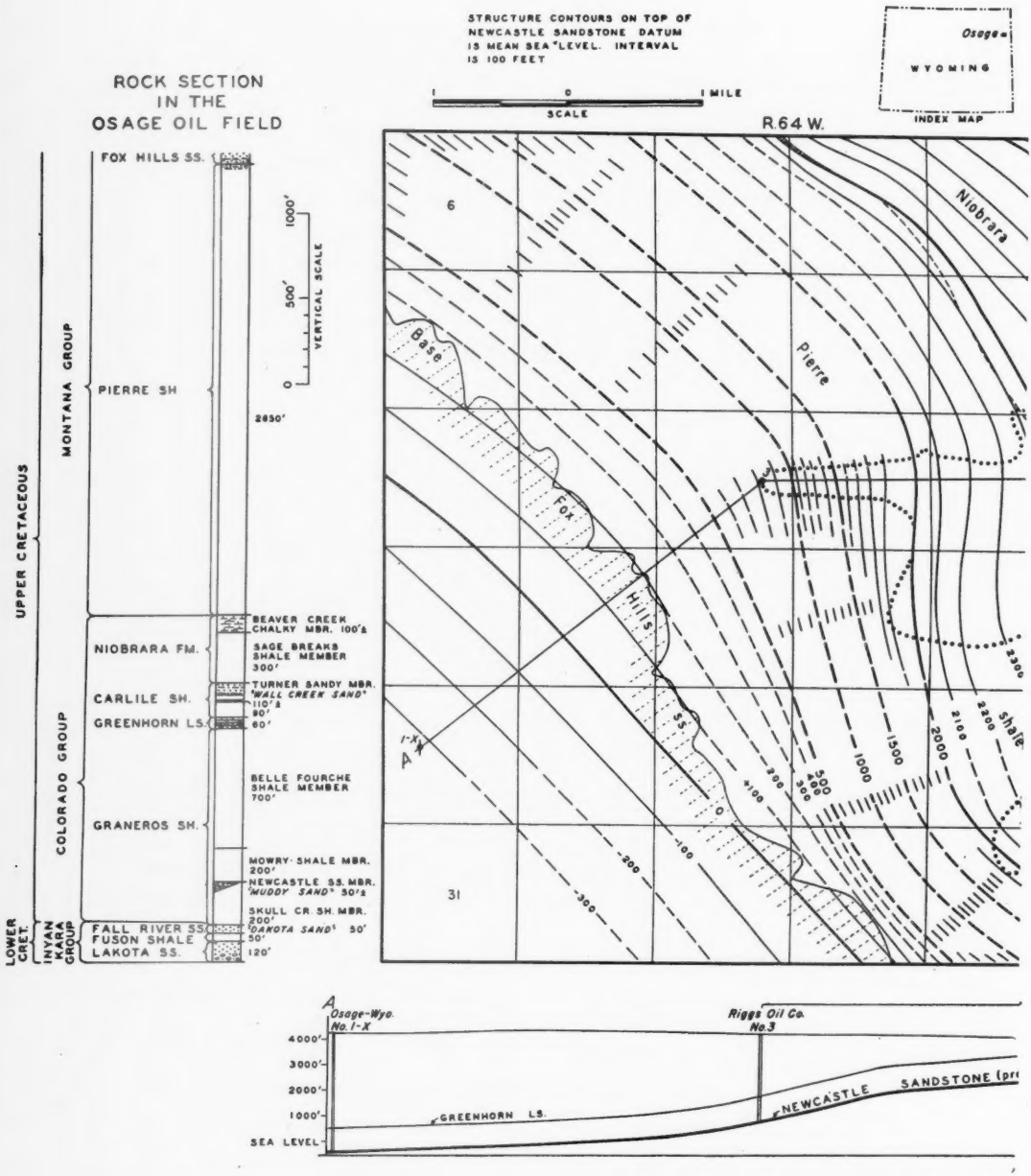
Wyoming contains 11 of the 26 monoclines and structural terraces that have produced oil and gas in the Rocky Mountain region, 10 of the 11 fields being on the rim of the Powder River Basin and one—Spring Valley—lying in the southwestern corner of the state. As shown in Table III, some of these monoclines and structural terraces are gentle and unfaulted; others are faulted slightly. In parts

[67] See also:
Dean E. Winchester, "The Oil and Gas Resources of New Mexico," *New Mexico School Mines and State Bur. Mines and Min. Res. Bull. 9* (1933), pp. 60–138.

[68] J. C. Miller and M. Q. Dannettell, "Preliminary Map Showing Geologic Structure of Bueyeros Carbon Dioxide Area, Harding County, New Mexico," *U. S. Geol Survey* (1938).

[69] J. C. Miller, "Carbon Dioxide Accumulations in Geologic Structures," *Amer. Inst. Min. Met. Eng., Tech. Pub. 841-I, 74* (1937), p. 16.

[70] John E. Blixt, "Cut Bank Oil and Gas Field, Glacier County, Montana," *Stratigraphic Type Oil Fields* (Amer. Assoc. Petrol. Geol., 1941), pp. 327–81.
C. E. Erdmann and N. A. Davis, "Preliminary Structure Contour Map of the Cut Bank-West Kevin-Border Districts, Glacier, Toole, and Pondera Counties, Montana," *U. S. Geol. Survey* (1939).



OSAGE OIL FIELD, WE

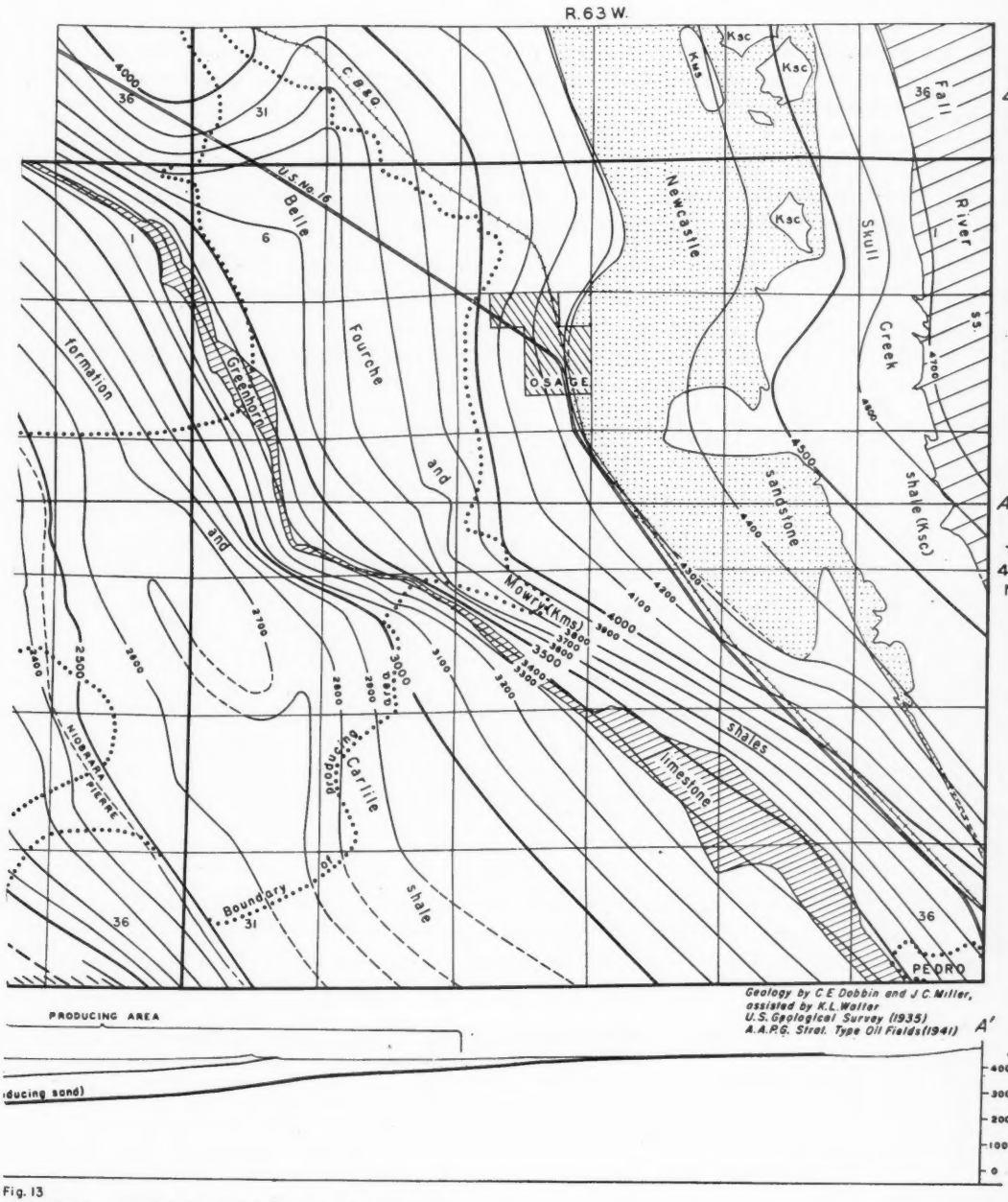


Fig. 13

STON COUNTY, WYOMING

of the Osage field (Fig. 13) dips as high as 20° occur in a narrow belt trending northwest across the field.[71] Although production from all other monoclines and structural terraces in the state is very small, that from the Osage field is relatively important.

COLORADO

Four of the 28 oil and gas fields in Colorado are on monoclines and structural terraces and one—Florence[72]—has had relatively important oil production since 1876. Accumulation is largely in joints and fissures in shale in areas of arrested monoclinal dip.

NORTHERN NEW MEXICO AND UTAH

All the four known monoclines containing oil and gas in northwestern New Mexico are unfaulted and dip very gently northeastward. The Kutz Canyon gas field is the only relatively important field in this classification in the state.

In Utah, oil has been produced in two gentle monoclines; namely, in the abandoned San Juan field in the southeastern corner of the state and in the very small Virgin field in the southwestern corner of the state.

STRUCTURAL NOSES

Although a few oil and gas fields in the Rocky Mountain region herein classified as low domes may actually be structural noses—such as the Plunkett field, Wyoming—there are seemingly only four authentic cases of structural noses producing oil in the region. The largest of these—the Border-Red Coulee[73] field in northern Montana—lies on one of the noses extending from the northwest end of Kevin-Sunburst dome and the Bears Den field 50 miles east is a terrace on an anticlinal nose plunging northeast from the Sweetgrass Hills uplift. The G. P. field in Wyoming—now shut in—is probably on a structural nose, and in the Canon City[74] field, Colorado, oil occurs in shale along an anticlinal nose plunging southward. None of the oil fields on anticlinal noses in the region is relatively important as a producer.

SUMMARY

Forty-one, or about 23 per cent, of the 180 oil and gas fields in the Rocky Mountain region are relatively important producers. Nineteen of these fields are on unfaulted anticlines and domes, 17 are on faulted anticlines and domes, and five are on monoclines and structural terraces. Four of the 19 important unfaulted

[71] C. E. Dobbin and J. C. Miller, "Osage Oil Field, Weston County, Wyoming," *Stratigraphic Type Oil Fields* (Amer. Assoc. Petrol. Geol., 1941), pp. 847–57.

[72] Ronald K. DeFord, "Surface Structure, Florence Oil Field, Fremont County, Colorado," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 75–92.

[73] C. E. Erdmann and J. R. Schwabrow, "Border-Red Coulee Oil Field, Toole County, Montana, and Alberta, Canada," *Stratigraphic Type Oil Fields* (Amer. Assoc. Petrol. Geol., 1941), pp. 267–326.

[74] R. K. DeFord, *op. cit.*, pp. 89–90.

structures produce only gas, 4 only oil, and 11 oil and gas. Three of the 17 faulted structures produce only gas, one only oil, and 13 oil and gas. Three of the 5 monoclines and structural terraces produce only oil, one oil and gas, and one only gas.

Age of Oil and Gas Zones (Fig. 14)

Although oil seemingly occurs in pre-Cambrian granite, quartzite, and other rocks at widely separated localities in the Rocky Mountain region, most of it apparently is derived from beds—mostly of Cretaceous age—beneath overthrust faults.[75] Showings of oil have been reported in Cambrian beds in a few isolated wells, in Devonian beds in the Sweetgrass arch and in Ordovician beds in the Cedar Creek (Baker-Glendive) anticline, Montana. Some geologists postulate that the deepest oil produced at Garland dome, Wyoming, comes from the Bighorn dolomite of Upper Ordovician age.

The Madison limestone, of lower Mississippian age, is the oldest proved commercial oil and gas zone in the Rocky Mountain region, yielding relatively large amounts of oil in the Kevin-Sunburst and Pondera fields, Montana, and in the Garland field, Wyoming. Other fields either producing or capable of producing oil from the Madison in varying amounts are the Soap Creek field, Montana, and the Frannie and Red Springs (Fig. 8) fields, Wyoming. In the small Devils Basin field, Montana, a little black oil is produced intermittently from the Van Duzen sand in the Heath formation (Mississippian), and some Mississippian oil was found in wells on the Cedar Creek (Baker-Glendive) anticline, Montana.

By far the greater quantity of Pennsylvanian oil produced in the Rocky Mountain region comes from the Tensleep sandstone in Wyoming.[76] At least 12 fields either produce or are capable of producing varying amounts of oil from the Tensleep in the Big Horn Basin, 4 on the southwestern flank of the Powder River Basin, and 3 in the Lost Soldier district. The Minnelusa sandstone of eastern Wyoming—part or all of which represents the Tensleep sandstone—produces large amounts of oil in the Lance Creek field and a small quantity in the East and West Mule Creek and Dewey[77] fields.

Pennsylvanian oil occurs in the Amsden formation at Soap Creek, Montana, in the Weber quartzite at Rangely, Colorado, and in the Hermosa formation in the San Juan field, Utah, and the Rattlesnake field, New Mexico.

In Wyoming, the Embar formation, of Permian age, yields oil at 12 localities in the Big Horn Basin, 6 in the Wind River Basin and vicinity, one on the south-

[75] Theodore A. Link, "Oil Seepages in Belt Series of Rocky Mountains Near International Boundary," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 8 (1932), pp. 786–96.
F. M. Van Tuyl and R. L. McLaren, "Occurrence of Oil in Crystalline Rocks of Colorado," *ibid.*, pp. 769–76.

[76] C. C. Branson, "Pennsylvanian Formations of Central Wyoming," *Bull. Geol. Soc. America*, Vol. 50, No. 8 (1939), pp. 1199–1226.

[77] J. D. Northrop, "Reconnaissance Map of the Dewey Area, Weston and Niobrara Counties, Wyoming, and Custer and Fall River Counties, South Dakota," *U. S. Geol. Survey* (1939).

TABLE VII

SUMMARY OF STRUCTURAL CONDITIONS UNDER WHICH OIL AND GAS HAVE ACCUMULATED IN ROCKY MOUNTAIN STATES

	Montana					*Wyoming*						*Colorado*				*N. New Mexico*			*Utah*	*Rocky Mtn. States*	
	Sweetgrass Arch and Vicinity	Bear-paw Mts. shallow thrust fault zone	Big Snowy Anticlinorium	South and East Mont.	Total	Big Horn Basin	Powder River Basin and Vicinity	Wind River and Shirley Basins	Laramie Basin and Vicinity	Green River Basin and Vicinity	Total	Great Plains	Northwest	Southwest	Total	San Juan Basin	Great Plains	Total		Grand Total	Gas Bearing Only
Anticlines and domes whose productive areas are either not faulted or only slightly faulted	4		1	5	10	22	13	13	11	4	63	6	12	2	20	5		5	6	104	28
Faulted anticlines and domes and fault blocks		6	2	2	10	11	4	3		9	27		3		3	3	1	4	2	46	20
Plunging anticlines and structural noses	2				2					1	1	1			1					4	
Structural terraces	2			1	3		3				3	2		1	3					9	2
Monoclines	2				2		7			1	8	1			1	4		4	2	17	4
					27						102				28			13	10	180	54

TABLE VIII

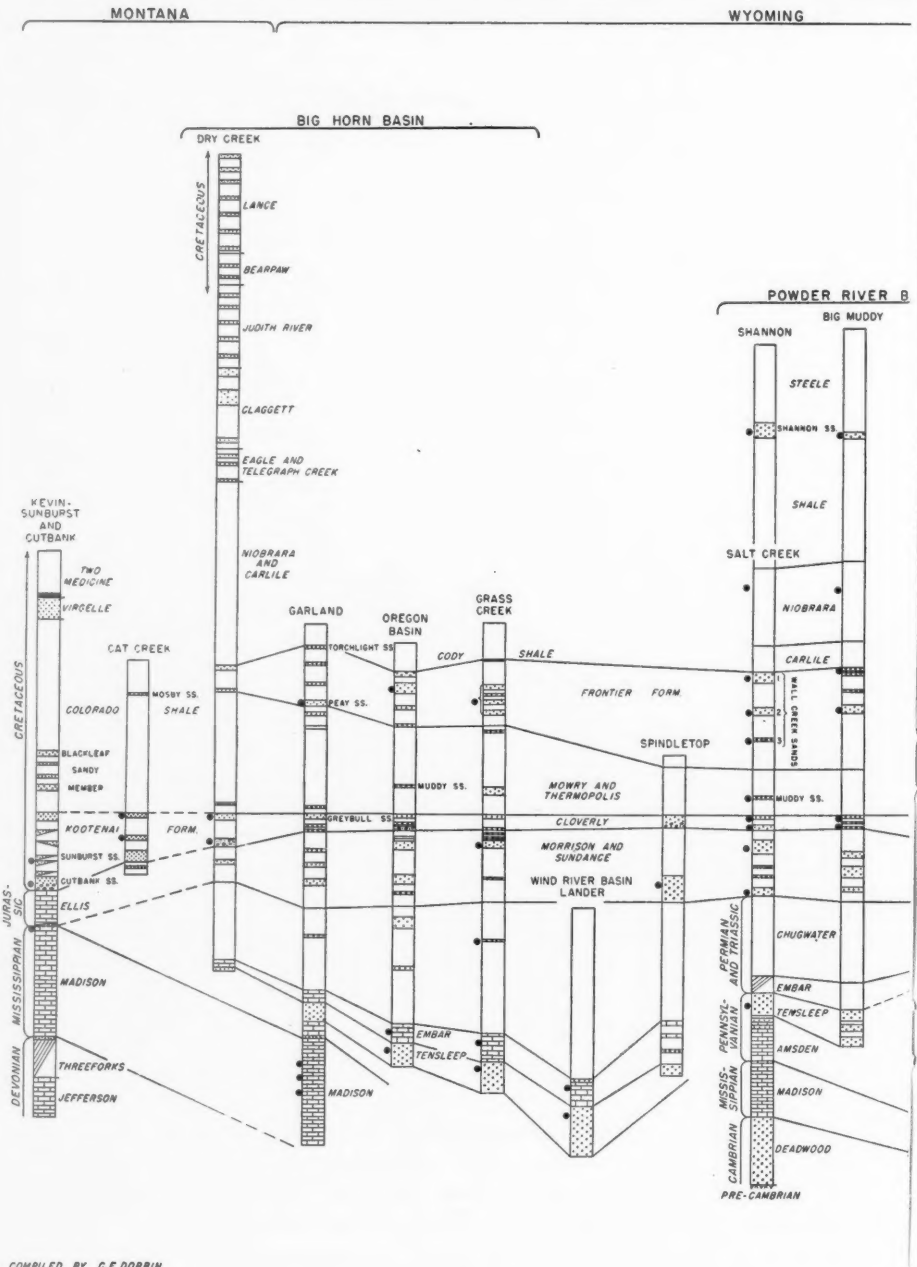
TABLE SHOWING NUMBER OF FIELDS IN WHICH EACH SYSTEM OR SERIES CONTAINS OIL AND/OR GAS ZONES UNDER VARIOUS SURFACE STRUCTURAL CONDITIONS

Age of Producing Zones	*Anticlines and Domes Whose Producing Areas Are Either Not Faulted or Only Slightly Faulted*		*Faulted Anticlines and Domes and Fault Blocks*		*Structural Noses*		*Monoclines and Terraces*		*State*
	Oil and Gas	Gas	Oil and Gas	Gas	Oil and Gas	Gas	Oil and Gas	Gas	
Oligocene							2		Wyoming
Eocene	2	2	1						Wyoming Colorado
Cretaceous	4 22 10 5	3 15 5 2	3 13 2 1	7 11 1 2	2 1 1		1 7 3 2	3 1 2	Montana Wyoming Colorado N. Mexico Utah
Upper Jurassic	2 7 2	2 7 3 1	2 1	1 1					Montana Wyoming Colorado Utah
Triassic	3 1	 1	1	1 1					Wyoming N. Mexico Utah
Permian	15	 1	7	1 1			 2		Wyoming Utah
Pennsylvanian	1 18 1 1	 1	7	1			2 1		Montana Wyoming Colorado N. Mexico Utah
Mississippian	4		3				1		Montana Wyoming
TOTAL NUMBER OF OIL AND GAS FIELDS									
	10 63 20 5 6		10 27 3 4 2		2 1 1		5 11 4 4 2		Montana Wyoming Colorado N. Mexico Utah

western flank of the Powder River Basin, and one in the south-central part of the state.

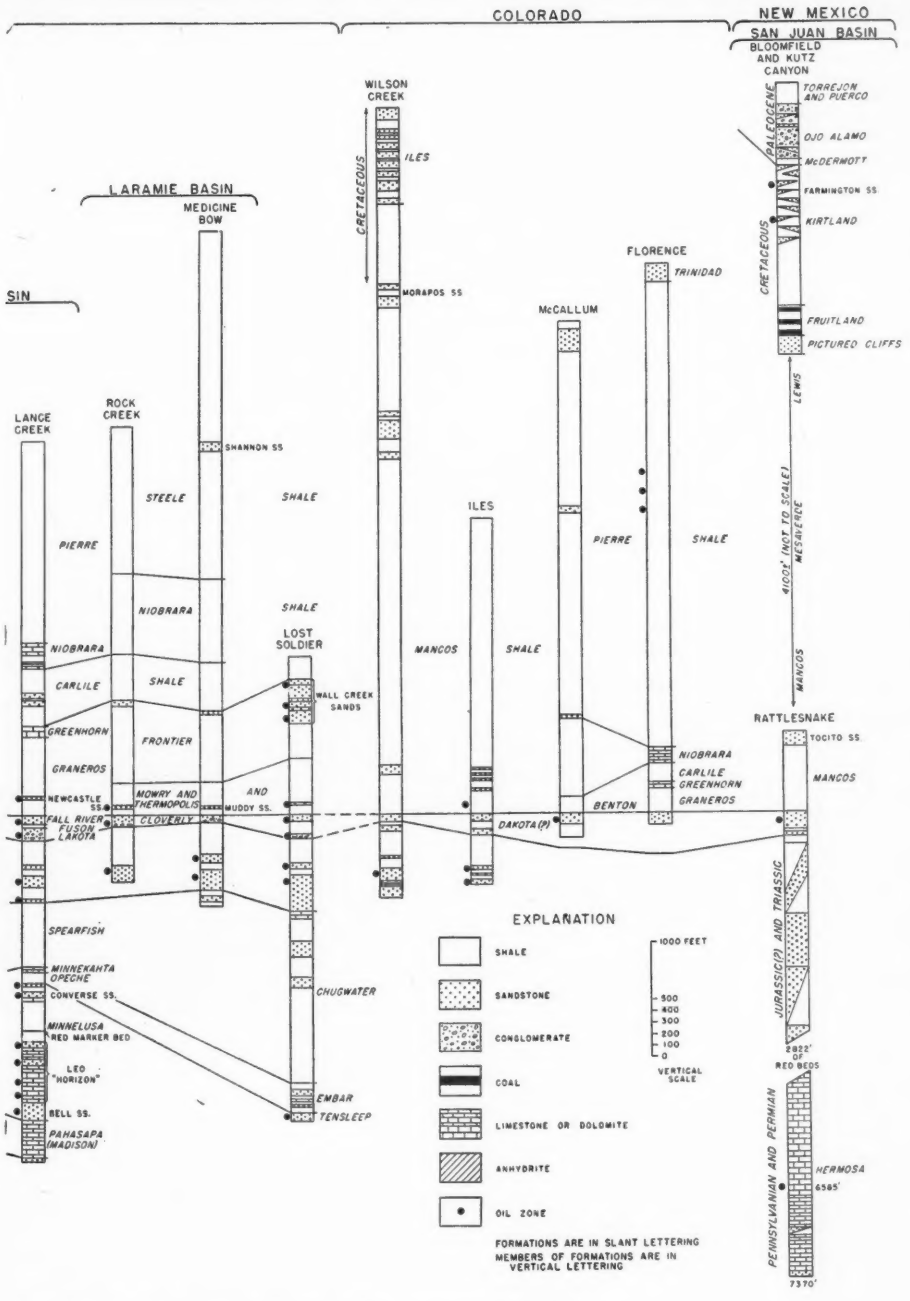
In Utah, the Coconino sandstone, of Permian age, yields gas containing 98.3 per cent CO_2 at Farnham dome,[78] and gas containing 1.31 per cent helium at Woodside dome.[78] In the San Juan area, southeastern Utah, sandstones in the Permian Rico formation have yielded small amounts of oil for many years, and

[78] C. E. Dobbin, "Geology of Natural Gases Rich in Helium, Nitrogen, Carbon Dioxide, and Hydrogen Sulphide," *Geology of Natural Gas* (Amer. Assoc. Petrol. Geol., 1935), p. 1068.



COMPILED BY C.E DOBBIN

Fig.14-COLUMNAR SECTIONS IN REPRESENTATIVE OIL AND GAS



FIELDS, ROCKY MOUNTAIN REGION, UNITED STATES

D.I.F.

in the Virgin field, southwestern Utah, small amounts of oil have been obtained in the top of the Kaibab limestone since 1907.

Commercial amounts of oil and gas have not been found in Permian beds in Montana, Colorado, and probably northern New Mexico.

The Chugwater formation, of Permian and Triassic age, has yielded relatively small amounts of black oil in the Grass Creek, Hamilton dome, Sage Creek, and Ferris fields, Wyoming, and the Santa Rosa (?) sandstone, of Upper (?) Triassic age, produces relatively pure carbon-dioxide gas in the Bueyeros area, Harding County, New Mexico. The Virgin field, in southwest Utah, produces very small amounts of oil from basal limestones of the Lower Triassic Moenkopi formation. Triassic formations do not yield commercial quantities of oil in Montana, Colorado, and New Mexico.

Oil and gas production from Jurassic beds in Montana comes only from the Upper Jurassic Ellis formation on the Sweetgrass arch and immediate vicinity.

Except for one relatively small oil well in the Byron field and relatively small quantities at Dewey, oil and gas production from Jurassic beds in Wyoming and Colorado is confined mostly to a belt, about 100 miles wide, trending northeast-southwest across the southeastern part of Wyoming and ending in northwest Colorado. Although the Upper Jurassic Morrison formation yields both oil and gas in a few fields, most of the Jurassic oil and gas come from the subjacent Upper Jurassic Sundance formation.

In the Garmesa field, Colorado, the Upper and Salt Wash members of the Morrison formation and the subjacent Kayenta formation and Wingate sandstone, of Jurassic (?) age, yield gas containing 20–61.05 per cent carbon dioxide.[79] In eastern Utah, the Morrison formation yields gas containing 7.16 per cent helium at Harley dome and also gas at Cisco and Ashley Valley.

Lower and Upper Cretaceous sandstones are the most widespread oil and gas zones in the Rocky Mountain region, producing either one or both of these commodities in 23 fields in Montana, 62 in Wyoming, 22 in Colorado, 12 in New Mexico, and 2 in Utah.

Commercial amounts of oil in Eocene beds have been found only in irregular, coarse non-marine sands comprising the Wasatch formation at Labarge, southwestern Wyoming, and at Powder Wash and Hiawatha, northwestern Colorado. The occurrence at Powder Wash and Hiawatha are particularly interesting and important, for all evidence indicates that the oil and gas are indigenous to the fluviatile Wasatch formation in which they are found.[80]

[79] C. E. Erdmann, "The Book Cliffs Coal Field in Garfield and Mesa Counties, Colorado," *U. S. Geol. Survey Bull. 851* (1934), p. 75.

[80] W. T. Nightingale, "Petroleum and Natural Gas in Non-Marine Sediments of Powder Wash Field in Northwest Colorado," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 22, No. 8 (1938), pp. 1040–47.
———, "Geology of Hiawatha Gas Fields, Southwest Wyoming and Northwest Colorado," *Geology of Natural Gas* (Amer. Assoc. Petrol. Geol., 1935), p. 361.

In the old Douglas field and in the Shawnee area, eastern Wyoming, minor amounts of oil and gas occur at relatively shallow depths either at or near the base of the overlapping White River formation of Oligocene age, the oil occurring in lenticular sands and conglomerates.

Character of Oil and Gas Zones[81]

Mississippian zones.—In the Kevin-Sunburst field, Montana, the Madison limestone of lower Mississippian age is about 800 feet thick and yields oil from caverns, fractures, small cavities, and intergranular pores in its weathered upper part subjacent to unconformable marine Jurassic shale, some of the Madison having been eroded in pre-Jurassic time.

In the Pondera field, Montana, the producing oil zone in the eroded and weathered upper 40 feet of the Madison is fine-grained granular dolomite grading downward into non-porous limestone, the porosity averaging 30 per cent and controlling production. The rather small quantity of oil yielded by the Madison at Soap Creek, Montana, comes from relatively uneroded limestone at the top of the formation.

The oil zones in the Madison limestone at Garland, Wyoming, are fine-grained, porous dolomite and limestone that occupy a zone about 250 feet thick lying below a non-productive uppermost part of variable thickness.

The Madison oil at Frannie, Wyoming, comes from the uppermost part of a thick limestone, and that at Red Springs, Wyoming, comes from a calcareous zone 58 feet thick, the top of which lies about 57 feet below the top of the Madison.

The small amounts of oil in the Heath formation, of the Big Snowy group, at Devils Basin, Montana, comes from lenticular sands, sandy shale, or limestone—the Van Duzen sand—and that in the Big Snowy group at Cedar Creek (Baker-Glendive), Montana, comes from limestone.

Pennsylvanian zones.—The Tensleep sandstone is 100–400 feet thick in Wyoming and, with its total or partial equivalent, the Minnelusa sandstone, yields most of the Pennsylvanian oil produced in the Rocky Mountain region. The Tensleep seemingly is very porous but actually large portions of it are so tightly and irregularly cemented that oil and water do not separate on a uniform water table, causing unusual occurrences of water in higher parts of a fold than of oil.

The Minnelusa sandstone is 1,100 feet thick at Lance Creek and yields much oil from several sandy zones separated by limestone, shale, and dolomite. Relatively small amounts of oil are yielded by a white sandstone in the Minnelusa at East Mule Creek and by limestone and shale at West Mule Creek.

[81] See also:

John G. Bartram, "Character of Producing Sandstones and Limestones of Wyoming and Montana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 9 (1932), pp. 864–80.

W. A. Waldschmidt, "Cementing Materials in Sandstones and Their Influence on Migration of Oil," *ibid.*, Vol. 25, No. 10 (1941), pp. 1839–79.

The Weber quartzite of northwestern Colorado yields the only Pennsylvanian oil produced in that state. It is at least 1,200 feet thick and, like its equivalent in Wyoming—the Tensleep sandstone—is white and buff fine-grained, cross-bedded quartzitic sandstone.

The only Pennsylvanian producing zone in Montana is a sandstone 80 feet below the top of the Amsden formation, though a lower sand in that formation has yielded some oil.

The oil produced from the Hermosa formation at Rattlesnake, New Mexico, comes from thick limestone, and that from the Hermosa in the old San Juan field, southeastern Utah, comes from sandstone interbedded with thicker limestone beds.

Permian zones.—The oil produced from the Embar formation in Wyoming comes from porous dolomite, chert beds, and in places thin sandstone beds that lie just below the non-porous 25–125 feet of limestone at the top of the formation. The oil yielded by the uppermost part of the Kaibab limestone in the Virgin field, southwestern Utah, comes from gray, cherty, jointed, and locally brecciated limestone. The oil from the Rico formation in the San Juan field, southeastern Utah, is from sandstone.

Triassic zones.—The small amount of oil produced from the basal part of the Moenkopi formation in the Virgin field, southwestern Utah, comes from thin limestone beds interbedded with red, gray, and yellowish shale. Similar amounts from the Permian and Triassic Chugwater formation in a few fields in Wyoming come from sandstone in redbeds.

Jurassic zones.—In the Kevin-Sunburst field, Montana, Jurassic oil is found in a stray sand in the Ellis formation, and in the small Bannatyne field near by it was found in sandstone 30–75 feet thick enclosed in black calcareous shale.

The oil-producing zones in the Sundance formation in Wyoming and northwest Colorado are pure, cross-bedded, ordinarily soft marine sands with uniform porosity. The very small amount of oil production from the Morrison formation in Wyoming comes from sandstone, as does the larger amount produced at Wilson Creek, Colorado.

Cretaceous zones.—Except for the oil found in fissures in relatively soft marine shale and from the harder, flinty Mowry shale at some localities, Cretaceous oil in the Rocky Mountain region is produced from irregular, medium-grained to conglomeratic lenticular sandstone beds of uneven porosity, the conglomeratic facies being largely confined to the Lakota sandstone and its equivalents.

Eocene zones.—The oil produced from the Wasatch formation at two localities in northwestern Colorado comes from irregular and lenticular fluviatile and lacustrine porous sandstone, and the oil from the Wasatch at Labarge and Dry Piney, southwestern Wyoming, comes from similar sandstone beds.

Oligocene zones.—The small amounts of Oligocene oil (White River formation) found at Shawnee and Douglas in eastern Wyoming comes from overlapping coarse, lenticular sands that lie in contact with Cretaceous and older beds.

Quality of Oil

The quality of the oil in the Rocky Mountain region bears no demonstrable relation to the dynamic metamorphism that the region has undergone. In many anticlines, light oil of paraffine base is produced from relatively shallow Cretaceous strata and heavy, black, "asphaltic" oil from Paleozoic beds. Some sharply folded anticlines (Fig. 8) yield black oil of 11°–18° gravity from Paleozoic beds and others with gentler dips yield 28°–45° gravity oil from the same zones.[82] It is evident, therefore, that in addition to metamorphism there are other factors responsible for the quality of the oil, such as differences in origin, weathering, natural processes of refining or filtration, deterioration as a result of contact with sulphate-bearing waters, and other changes during and after migration.

The lowest-gravity oil produced commercially in the region from Mississippian strata is the 11° oil in the asymmetrical and rather sharply folded Red Springs anticline (Fig. 8) in the Big Horn Basin, Wyoming. The oil zone lies about 950 feet below the surface and 57–115 feet below the top of the Madison limestone. In the other seven areas of Mississippian production in the region, the oil is of "asphaltic base," ranging in gravity as high as the 31°–37° oil in the top of the Madison limestone in the Kevin-Sunburst and Pondera fields, Montana. In the former field, superjacent Upper Jurassic beds yield 38° paraffine oil and Lower Cretaceous beds produce 34°–38° paraffine oil. In the Garland field (Fig. 12), Big Horn Basin, Wyoming, the unfaulted Madison limestone yields 19° black oil at a depth of about 4,000 feet, and the Upper Cretaceous Frontier formation has produced relatively small amounts of 40° oil at depths of 500 feet and greater. The best production at Garland occurs in a zone as much as several hundred feet thick whose top lies a similar depth below the top of the Madison.

The relatively large amounts of oil produced from the Tensleep sandstone, of Pennsylvanian age, in Wyoming is mostly of an "asphaltic base," the lowest gravity being the 14° oil in the highly compressed Fourbear anticline in the Big Horn Basin. The highest-gravity Pennsylvanian oil in the region is 42°–45° black and brown oil in the Minnelusa sandstone—equivalent (?) of Tensleep sandstone—in the Lance Creek field, and the next lowest important production is the 35° brownish green oil in the Tensleep sandstone at Wertz and Lost Soldier. The Minnelusa sandstone yields some 23° black oil in the East Mule Creek field and 34° black oil in the West Mule Creek field, only $3\frac{1}{2}$ miles distant.

The only other prominent exception to the general occurrence of low-gravity black oil in Pennsylvanian beds in the region is the 42° oil in the Hermosa formation in the Rattlesnake field, San Juan Basin, New Mexico, where Cretaceous beds about 5,900 feet higher produce oil of 76°–63° gravity.

In the Salt Creek oil field, Wyoming, Tensleep oil is 27° gravity and black,

[82] John G. Bartram, "Oil Gravities in the Rocky Mountain States," *Problems of Petroleum Geology* (Amer. Assoc. Petrol. Geol., 1934), pp. 157–76.
C. E. Dobbin, "Carbon Ratios and Oil Gravities in the Rocky Mountain Region of the United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (1929), pp. 1249–51.

whereas green oil ranging from 30° to 39° in gravity is produced from Upper Jurassic and Cretaceous beds. In the Grass Creek field, Wyoming, the Tensleep oil is 25° gravity and black, whereas Triassic and Jurassic oils there are 18° and 16° gravity, respectively, and black, and Upper Cretaceous oil is 45° gravity.

Except for small amounts of dark brown 24°–30° gravity oil produced in the Virgin field, southwestern Utah, all Permian oil is produced in Wyoming, largely from the Embar formation, and in conjunction with Tensleep production. The oil is black and averages 23° in gravity, though 32° black oil occurs at Bolton Creek.

Thin limestones and interbedded gray and red shale at the base of the Moenkopi formation of Lower Triassic age yield small amounts of 24°–30° dark brown oil in the Virgin field in southwestern Utah, but all other production in that series is confined to four fields in Wyoming, where the black oil occurs in sandstone interbedded in redbeds and has a gravity of 18°. At Hamilton dome, the Triassic Chugwater oil is of about the same gravity as Permian and Pennsylvanian oil, but at Ferris oil from fissures in Upper Cretaceous shale above is of 36° gravity.

Upper Jurassic oil in the region comes largely from sandstones in the marine Sundance formation, or close equivalents, although a relatively large amount is produced from the overlying continental Morrison formation in the Wilson Creek, Moffat, and Iles fields in northwestern Colorado, and lesser amounts in several fields in Wyoming. Black oil of 16° gravity occurs in the Morrison at Grass Creek, Wyoming, and 23°–27° gravity black oil in the Ellis formation in the Bannatyne field, Montana, where the producing zone is a marine sandstone 30–75 feet thick enclosed in marine shale. In the Spindletop, Bolton Creek, and Poison Spider fields, in east-central Wyoming, black Sundance oil has a gravity of about 21°.

The highest gravity oil in the Sundance in the region is the 62° straw- and amber-colored oil found at a depth of about 5,275 feet in the first and second Sundance sands in the Medicine Bow field, Wyoming. Nine miles southeast and about 2,100 feet structurally higher the Sundance yields 34° gravity oil in the Rock Creek field.

In the Lance Creek field, Wyoming, the first Sundance sand contains 38° gravity black oil at an average depth of 3,700 feet, and about 160 feet lower, the basal Sundance sand produces large amounts of 47° gravity green oil.

Although small amounts of black oil are found in Cretaceous rocks in some widely scattered areas in Wyoming and in one field in Montana, almost all the oil from that series is relatively high-gravity green oil. In the small Mosser field, southern Montana, the Greybull sandstone member of the Cloverly formation at a depth of 1,000 feet yields relatively small amounts of 22° gravity black oil. In the Cole Creek field, Wyoming, the Dakota (?) sandstone at a depth of 7,900 feet yields green oil of 37° gravity and the Lakota sandstone, 100 feet lower, yields black oil of 32° gravity. Small amounts of black oil of 19° gravity are produced from the Muddy sand at a depth of 900 feet in the Big Hollow field, Wyoming, and in the Billy Creek field, a small quantity of green oil of 20° gravity is yielded

by the Frontier formation at a depth of 3,217 feet, in conjunction with the production from the same formation of exceedingly dry gas.

The highest gravity oil produced from Cretaceous strata in the region is the 76° oil that comes from the Dakota (?) sandstone at a depth of 730 feet in the Rattlesnake field, New Mexico, which, in 24 hours, weathers to about 63° gravity, which is the gravity of the oil at the near-by Hogback field in the same zone. As previously stated, Pennsylvanian beds 5,900 feet lower at Rattlesnake yield oil at 42° gravity. Other occurrences of relatively high-gravity oils in Cretaceous strata include the 48°–52° gravity oils in the Cat Creek and Dry Creek fields, Montana, and the 57° gravity oil in the small Aztec-Bloomfield area, northwest New Mexico.

The relatively large amounts of Eocene oil found in the Wasatch formation at depths of 2,152–5,032 feet in the Powder Wash field, Colorado, and the smaller quantity at depths of 1,600–2,800 feet in the near-by Hiawatha field is of 38° gravity. In the Labarge field, southwestern Wyoming, the light brown oil in the coarse, irregular, lenticular overlapping sandstone beds of the Wasatch is 17°–45° gravity and is found at depths of 650–1,100 feet.

Table IX shows that oil produced in the same field from beds of different ages and character may have relatively similar gravities in some fields, such as Kevin-Sunburst, Lance Creek, and Lost Soldier, whereas that in other areas, such as Grass Creek and Rattlesnake, varies widely in gravity.

Carbon Ratios

The carbon-ratio theory, as developed and applied in the Appalachian region containing high-rank Carboniferous coals, can not be indiscriminately applied in the Rocky Mountain states, where most of the Cretaceous and early Tertiary coals are low in rank, for (1) most of the coal beds lie at shallow depths and have suffered incipient weathering and (2) carbon ratios, as ordinarily calculated, do not show satisfactorily the rank of low-rank coals.

The abnormally high carbon ratios for low-rank coal in the Rocky Mountain region results from the failure to recognize moisture as an essential constitutent of the "volatile matter" of coal. Were the analyses used on an as-received ash-free basis, the lignites and sub-bituminous coals would probably indicate the degree of metamorphism rather closely. It is believed, though, that the carbon ratios of the much restricted low-volatile bituminous and higher-rank coals of the region probably indicate nearly the same degree of metamorphic intensity as that indicated by the carbon ratios of the eastern Paleozoic coals.

ADDENDA

WYOMING

Pilot Butte field, Sweetwater County.—In April, 1942, black oil of 24° gravity was discovered in the Tensleep sandstone (Pennsylvanian) at a depth of about 6,250 feet.

TABLE IX

SUMMARY OF PRINCIPAL FIELDS PRODUCING OIL AND GAS FROM ZONES OF DIFFERENT AGES IN ROCKY MOUNTAIN REGION

State		Field	Structure	Principal Producing Zones								Remarks
				Age	Formation	Member	Lithology	Depth (Feet)	Thickness (Feet)	Contents	Gravity A.P.I. at 60°F.	
Montana		Kevin-Sunburst	Broad unfaulted dome on Sweetgrass Arch with total closure of 850 feet.	Lower Cretaceous	Kootenai	Sunburst sand	Lenticular sandstone	1100–1735	5–50		34–38	Oil and gas pools controlled by sand irregularities.
				Upper Jurassic	Ellis	Stray sand	Lenticular sandstone	1200–1600	1–5	Oil and gas	38	Accumulation controlled largely by erratic porosity caused by pre-Jurassic weathering of surface of Madison limestone.
				Mississippian	Madison ls.[a]	Top	Eroded and weathered limestone and dolomite	1340–1900	2–19		31[b]–37	
Wyoming	Big Horn Basin	Garland	Extremely faulted anticline at surface with about 2,500 feet of closure.	Upper Cretaceous	Frontier	Peay ss.	Medium to coarse-grained irregular sands	500–1960	30	Oil and gas	40	Frontier oil accumulated in a fault block. Some gas in the Morrison and Chugwater. Embar-Tensleep gas is sour. Some geologists think some of oil is from the Big Horn dol. (Ordovician). Madison limestone is unfaulted.
				Lower Cretaceous	Cloverly			1600–1900	30	Gas		
				Permian-Pennsylvanian	Embar-Tensleep		Porous, cherty dolomite and uniform quartz sand.	3000–4150	250			
				Mississippian	Madison ls.[a]		Fine-grained, porous dolomite	4250	350±	Oil and gas	19[b]	
		Grass Creek	Elongated, asymmetrical, unfaulted anticline. Closure 2,400 feet.	Upper Cretaceous	Frontier[a]		Three to six sands	315–1300	5–50 each	Oil and gas	45	Muddy and Greybull sands produce some gas.
				Upper Jurassic	Morrison		Sandstone	1887	29		16[b]	
				Triassic, etc.	Chugwater		Sandstone in redbeds	3100	10	Oil	18[b]	
				Permian-Pennsylvanian	Embar-Tensleep[c]		Porous, cherty dolomite and uniform quartz sand	3565–4400	70+		25[b]	
	Powder River Basin	Salt Creek	Large dome cut by many transverse faults. Closure 1,600 feet.	Upper Cretaceous	Steele, Niobrara and Carlile		Oil in shale fissures	200–800	50		39	Much water and very little 22°-gravity oil in the Madison limestone. Faults extend to at least 3,000 feet. Some oil in the Muddy and Dakota sands.
					Frontier	First Wall Creek sand	Fine-grained sand	930–1050	90–160		39	
						Second Wall Creek sand[a]	Fine-grained sand and bentonite	1330–2100	50–90	Oil and gas	38	
						Third Wall Creek sand	Lenticular, tight gray sand	1600–1700	0–30		37	
				Lower Cretaceous	Cloverly	Lakota sand	Shale	1800–2100	25		35	
							Conglomerate and sand	2300–2550	50		37	
				Upper Jurassic	Morrison			2320–2420	115		30	
					Sundance		Three sand benches	2800–3000	60		35	
				Pennsylvanian	Tensleep ss.		Uniform, cross-bedded sand	3820–4120	185		27[b]	

Wyoming	Power River Basin	Lance Creek	Broad dome on an elongated, unsymmetrical anticline. Closure about 650 feet.	Lower Cretaceous Upper Jurassic Pennsylvanian	Fall River ss. Sundance[a] Minnelusa ss.[a]	First sand Basal sand Converse sd. Leo sands	Two sands separated by shale Thin sands, sandy ls., –sandy dolomite, limestone, and porous dolomite	3200– 3700 3860 4400 5200	26–50 15–50 40–60 40–139 230	Oil and gas	42 38[b] 47 42[b] 45	Good showing of oil in Wall Creek in some wells. Some oil in the Newcastle sandstons (Muddy sand). Lakota produced much ga in one well.
		Lost Soldier	Elliptical faulted dome with 3,500 feet of independent closure.	Upper Cretaceous Lower Cretaceous Upper Jurassic Pennsylvanian	Frontier Cloverly[a] Sundance[a] Tensleep ss.[a]	Wall Creeks	Third and fourth sands Pure, cross-bedded sand Pure, quartz sand	195–600 1500 1900 4250	90 ft. each 40-80 180 80+	Oil and gas	31 35	Some oil in the Mowry shale and in the Morrison. Faults extend down 1,500 to about 2,000 feet.
Colorado		Rangely	Huge, unfaulted symmetrical dome with closure of 1,200+ ft.	Upper Cretaceous Pennsylvanian	Mancos shale Dakota (?) ss. Weber quartzite (Tensleep ss.)		Fractures in shale Pure quartz sand	372–1000 3000 5704		Oil Gas Oil (1 well)	41 33	Production in Mancos shale is where gentle dip changes to steep dips.
New Mexico		Rattlesnake	Elongated, almost symmetrical dome. Faulting minor.	Upper Cretaceous Pennsylvanian	Dakota (?) ss. Hermosa		Four benches of erratic sands separated by sandy shale Limestone and dolomite	730 6585–6771	8–200 8–35	Oil	76–63 42	Surface closure about 100 feet. Dakota (?) production due to sand lensing and local doming. Tested to Cambrian.

[a] Principal oil zones in field.
[b] Black in color.

Sherard dome, Carbon County.—In April, 1942, a gas well was completed for production in the basal Cloverly formation (Lower Cretaceous) at a depth of 2,950 feet.

Canyon Creek dome, Sweetwater County.—In August, 1941, a relatively small gas well was completed in the Wasatch formation (Eocene) at a depth of 2,688 feet.

Horse Creek dome, Laramie County.—In October, 1942, oil was discovered in the Lakota sandstone (Lower Cretaceous) at a depth of 5,451 feet.

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GEOLOGY OF WASSON FIELD, YOAKUM AND GAINES COUNTIES, TEXAS[1]

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ABSTRACT

The Wasson field is near the central part of the Staked Plains or "Llano Estacado," in southern Yoakum and northwestern Gaines counties, Texas. It occupies a triangular area 15 miles long and 14 miles wide, containing approximately 55,000 acres or 86 square miles, and is defined at only a few points by dry holes.

Geologically, the field lies on the extended axis of the Central Basin platform, but appears to be separated from it by a trough in northern Gaines County. For the purpose of this paper the structural-stratigraphic feature under discussion is referred to as part of North Basin platform.

Two major axes, one trending N. 60° W., the other N. 30° E., combine with several minor parallel axes to form a compound structure. The combined effect of the structural elements gives the whole the appearance of a terraced platform tilted northeast by post-Permian movement.

The stratigraphy is typical of West Texas, in that massive, porous dolomites with few clastics are present and grade basinward into thicker sections of interbedded dolomite and anhydrite containing more clastic material.

The section penetrated by wells consists of: Recent, Tertiary, Cretaceous, Triassic, and Permian rocks. The reservoir is in porous dolomite 300–600 feet below the top of the San Andres formation. Detailed examination of the well cuttings show the body of the reservoir to have a reef-like cross section which may be accounted for by (1) physico-chemical deposition on a submarine "high," and (2) reef growth with attendant chemical deposition and recrystallization of the dolomite.

The combination of Permian structure and stratigraphy appear to have controlled the permeability, porosity, and the accumulation of fluids. Later folding has modified the position of these fluids somewhat but for the field as a whole there is no direct relationship between the present structural elevation and the ability to produce oil.

The discovery well, the Honolulu Oil Corporation and the Davidson Drilling Company's Bennett No. 1, found oil on September 28, 1935. Development has been continuous since 1936 and 42,631,627 barrels of oil had been recovered from the field by Jan. 1, 1943.

INTRODUCTION[3]

Many of the dolomite fields of West Texas have much in common with respect to the occurrence of oil from structural, stratigraphical, and lithological viewpoints. The structural problems are usually not difficult because most of the structural traps are simple anticlinal or monoclinal folds. Complicating factors such as faulting or slumping are present in only a few fields. On the other hand, the relationship of structure, stratigraphy, and lithology is more complex—chiefly because of the difficulty of identifying stratigraphic changes and lithologic variations as measurable and definable units. This problem in the Wasson field is complicated by the lack of clastic beds for use as markers and by the apparent uniformity of dolomite in the sequence. These difficulties necessitate textural studies as a means of correlation within the reservoir. Because of the rapid rate at which the field was drilled microscopic analysis of well cuttings and study of drill-

[1] Presented before the Association at Houston, Texas, April 3, 1941. Manuscript received, June 13, 1942.

[2] Honolulu Oil Corporation.

[3] Report with maps was completed in February, 1941, when the field had 1,031 wells. No attempt has been made to include subsequent information except some statistical data which have been revised to Jan. 1, 1943.

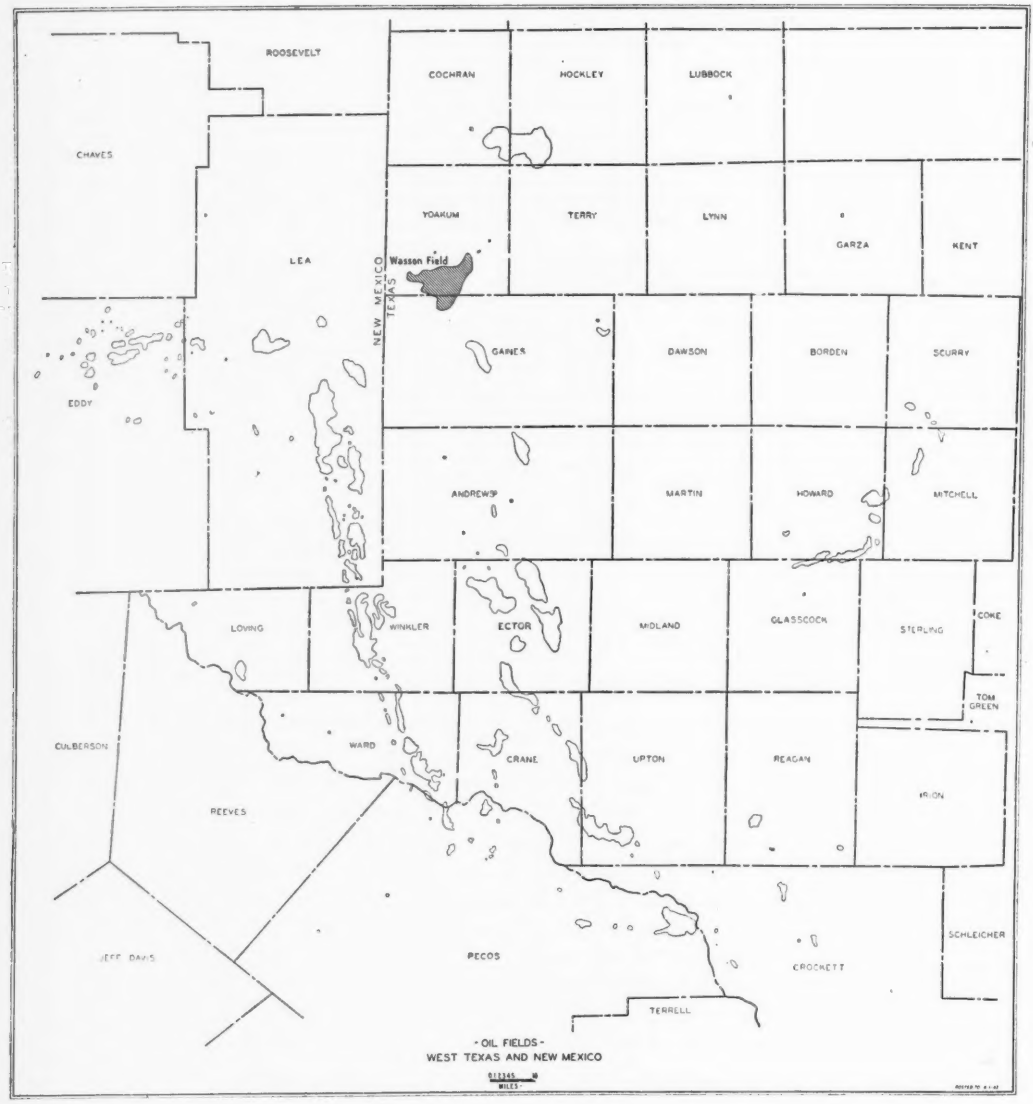

FIG. 1.—Map of part of West Texas and New Mexico, showing relative position and size of Wasson field to other fields.

ing-time logs were the only practical sources of information. Experience indicates that the determination of the stratigraphic, lithologic and structural relationships of a West Texas dolomite field require close and continuous control with detailed microscopic analysis of good samples.

Location and Physiography

The Wasson field is in the central part of southern Yoakum County with its southern end extending into the northwestern part of Gaines County (Fig. 1). The present western limits extend to within 5 miles of the Texas-New Mexico boundary.

Physiographically the field is located in the south-central part of the semi-arid and featureless High Plains, "Llano Estacado," of western Texas and New Mexico. The topography is characterized by gentle depressions and elevations—the result of "blow-outs," caliche caps, and differential erosion. But these minor features are lost on the typically "straight-edge" horizon of the High Plains. The surface slopes southeast from an elevation of 3,700 feet above sea-level on the west to 3,520 feet on the east side of the field (Fig. 2). Several shallow dry ravines, remnants of less arid times, traverse the field from northwest to southeast. The largest of these is McKenzie Draw.

Surface material consists of wind-blown sand, caliche, and a thin soil mantle. Very little of the land is cultivated.

History

For the purpose of reference, the field has been divided into development sectors (Fig. 2) in each of which activity spread from an outlying well, as a nucleus, into a sector of the field. Eventually the sectors joined and resulted in the field as now constituted. The sectors have no relation to different geological features.

The first well to encounter oil in the area and the first well to test the San Andres in Yoakum County was the C. J. Davidson and the Honolulu Oil Corporation's Bennett No. 1 (now the Honolulu-Cascade's Bennett No. 1-678), Sec. 678, Block D, John H. Gibson Survey, Yoakum County. At the time of its spudding, April 4, 1935, the nearest production was in the Hobbs field in New Mexico, 35 miles southwest. One well, Weekly's Knight No. 1, in Sec. 791, one mile west of the western limits of the field, had been abandoned in August, 1929, before reaching the San Andres. Another test, the Texas Consolidated-Texas Pacific's Jones No. 1 in Gaines County, midway between Hobbs field and the discovery well drilled in 1932 had been found structurally low.

The Bennett well was drilled with rotary tools to a depth of 2,424 feet to reduce the number of strings of casing needed and to avoid the cavy Triassic and Permian redbeds which are hazardous to cable-tool drilling throughout West Texas and New Mexico. The first showing of oil was encountered on September 28, 1935, at 5,085 feet where the hole filled with 700 feet of oil. The volume of gas was estimated as $\frac{1}{2}$ million cubic feet per day. After 7-inch casing had been ce-

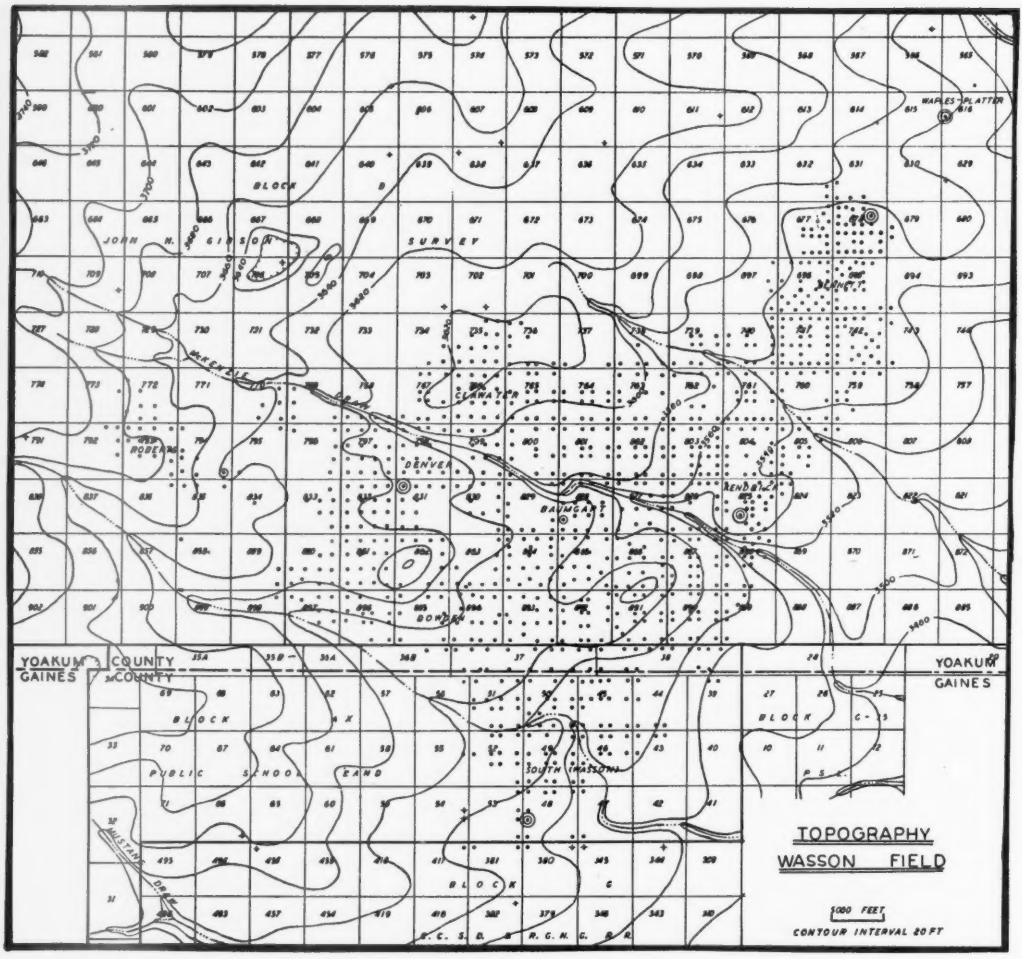

FIG. 2.—Map showing topography of Wasson field. Contour interval, 20 feet.

mented in the well, 3,700 feet of oil was present. The well was then drilled to 5,116 feet and treated with 1,000 gallons of acid and as a result a flow of 17 barrels of oil per day was obtained. Drilling was again resumed and increases were logged to a final depth of 5,282 feet. Following the shooting of the pay-section with nitroglycerine, the well received an initial gauge of 234 barrels of oil per day. In 1937 the well was worked over, a $5\frac{1}{2}$-inch liner cemented and the well treated with a total of 10,500 gallons of acid in three stages which increased the official potential to 428 barrels of oil per day.

Immediate drilling activity did not follow the drilling of the discovery well for several economic reasons: lack of pipe-line outlet, remoteness of pipe-line stations with attendant high trucking costs, and the low market price of crude oil. The nearest pipe-line station was the Humble Pipe Line Company's terminus at the Means pool in Andrews County, necessitating a 60-mile haul. Nine months elapsed before the second well, the Texas and Pacific Coal and Oil Company's Bennett No. 1, was completed. This well was located approximately 2,200 feet west of the discovery well.

A second discovery[4] well, 12 miles south, was brought in as a producer in June, 1937. This test, the A. G. Carter and the Continental Oil Company's Wasson No. 1, is in Sec. 48, Block AX, P. S. L. Survey, Gaines County. High structural position with respect to the Bennett well and the showing of gas in the rotary drilling mud portended another discovery before the oil-saturated cores were recovered at a depth of 4,810 feet. The total depth of 4,959 feet was reached and an official initial potential gauge of 333 barrels of oil per day was established. Upon the completion of this well, active development began in the Bennett and the South sectors—largely in the form of forced offset wells.

A third discovery well was completed, in September, 1937, the Denver Producing and Refining Company's Whittenburg No. 1, Sec. 831, Block D, John H. Gibson Survey. An official initial potential gauge of 892 barrels of oil per day was given this well, drilled to 5,001 feet. The resulting pool was designated the Denver pool and completed the triangle of operations which formed the base for extensions and development. At this point in the field's history several dry holes limited the southward expansion of the South sector but the gap between the South and the Denver sectors was gradually closed. High structural position and the performance of wells between these two sectors indicated the presence of a gas cap. Concurrent with, and giving impetus to, these developments was the first pipe line laid into the area from Hobbs, New Mexico, by the Humble Pipe Line Company, in November, 1937.

Figure 3 shows the rate at which wells were completed monthly and the stimulus rendered by pipe-line outlets. During the peak of drilling activity, reached at the close of 1939, nearly 50 wells were completed monthly. By July 1, 1942, 1,358 wells had been drilled in an area of approximately 55,000 acres, or 86 square miles, and with a perimeter of 49 miles. In area the Wasson pool is exceeded only by the East Texas field, and the Slaughter field of Hockley, Cochran, and Terry counties.

Most of the expansion has been in the form of offset drilling, but several extensions are noteworthy. The Texas Company's Walker No. 1, Sec. 794, was completed in January, 1938, extending the producing area several miles westward. This test and the Shell Oil Company's Roberts No. 1 started activity in the Roberts sector. Meanwhile the Denver sector was extended eastward by the

[4] The pool which developed as a result of this discovery was the original Wasson pool. In this paper the term "south sector" has been used to avoid confusion between the original part and the present whole.

completion of the Shell Oil Company's Baumgart No. 1-A which commenced the Baumgart sector activity. Lastly the completion of the Honolulu Oil Company's Kendrick No. 1,[5] Sec. 825, formed the nucleus of activity which ultimately united the Bennett-Wasson-Denver areas into one. The Texas Railroad Commission officially joined these areas into the Wasson field on December 1, 1939.

Activity during the first part of 1942 was confined to extending the field north and west. A gradual structural slope on the north gives a more favorable aspect to expansion of the field in that direction. The proved area is almost fully developed. Another phase of activity has been the deepening of earlier wells to include the 100–150 feet of additional reservoir revealed by the Honolulu's Kendrick No. 1.

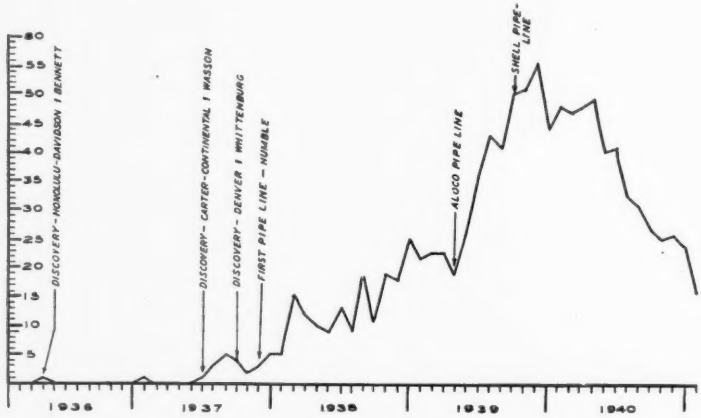

FIG. 3.—Chart showing monthly rate of wells completed.

The potentialities of the field were greatly increased by a deep test in the South sector in Sec. 50, Block AX, P. S. L. A. G. Carter's Wasson No. 5-D was drilled through the regular Wasson pay zone and exposed a 671-foot dolomite section, commencing at 6,210 feet and extending downward to the total depth of 6,881 feet, which yielded 230 barrels of 32.1° gravity oil on a 7-hour test. The test was made through ¾-inch choke on 2½-inch tubing after a total acid treatment of 18,500 gallons. The producing zone occurs 1,200 feet below the regular Wasson zone. Geological information has not been released on this well but the oil is probably coming from within the Yeso-Clear Fork group. This new zone has received the name "Wasson Deep." On the same lease and 1,800 feet north another deep test, Carter's Wasson 4-D, was drilled to a total depth of 11,108 feet in

[5] This test was of additional interest in that it revealed the hitherto unknown water level to be at least 100 feet below the ordinary depths penetrated by the wells on the west.

Ellenburger dolomite. After the lower formations were tested the well was plugged back to 7,433 feet and the casing was gun perforated from 7,055 to 7,375 feet. After being treated with 6,000 gallons of acid in two stages the well flowed at the rate of 511 barrels of 34° gravity oil per day through ½-inch choke on 2½-inch tubing by gas lift in December, 1941.

A third deep well to be drilled in or near the field was Murchison *et al.* Sawyer No. 1, Sec. 702. This well was first abandoned after making showings of oil in the regular Wasson producing zone where it delimits the field on part of the north side. In the late part of 1940 the operators commenced deepening the well with the object of testing the "Wasson Deep" section. Mechanical difficulties and a non-porous section at 6,850 feet were discouraging and the test was again abandoned.

Subsurface Stratigraphy

The mechanical methods of drilling have had a pronounced effect (and a sometimes discouraging one) on stratigraphical and lithological studies. Well cuttings are customarily kept only through the following parts of the section: top of anhydrite, Yates sand, Yoakum dolomite or "brown lime" as termed by those working in the area, and top of San Andres or "solid lime." For these reasons it has been necessary to construct a composite section (Fig. 4) from the most representative data in the various parts of the area. Weekly's Knight No. 1, Sec. 791, is the only well in the immediate vicinity of the field which drilled the upper redbed section with cable tools, while the Bennett discovery well and near-by Texas and Pacific's Bennett No. 1, mentioned earlier, are the only two wells in the field which drilled the Ochoa, Whitehorse, and the upper San Andres units with cable tools.

Percentage logs are commonly employed and the section and detailed cross sections are constructed on this basis.

In general the section may be divided into four distinct environmental types of deposits: (1) a relatively thin blanket of coarse sands, limestones, and shales of Tertiary and Cretaceous ages; (2) red sands and shales of the Triassic and Permian; (3) evaporites composed of salt, potash, gypsum, and anhydrite of the Ochoa and Whitehorse units; and (4) chemical and organic deposits, mainly dolomite, of the San Andres group.

TERTIARY

Ogallala formation (?).—Coarse buff, pink, and gray sands and vari-colored gravels, all loose or poorly consolidated, underlie the Recent wind-blown sand and caliche. These have shown a marked variation in composition and thickness in the few sets of samples saved from this part of the section. Many of the sandstones have been silicified to hard quartzites and the gravels show evidence of a secondary opaline precipitation of silica.

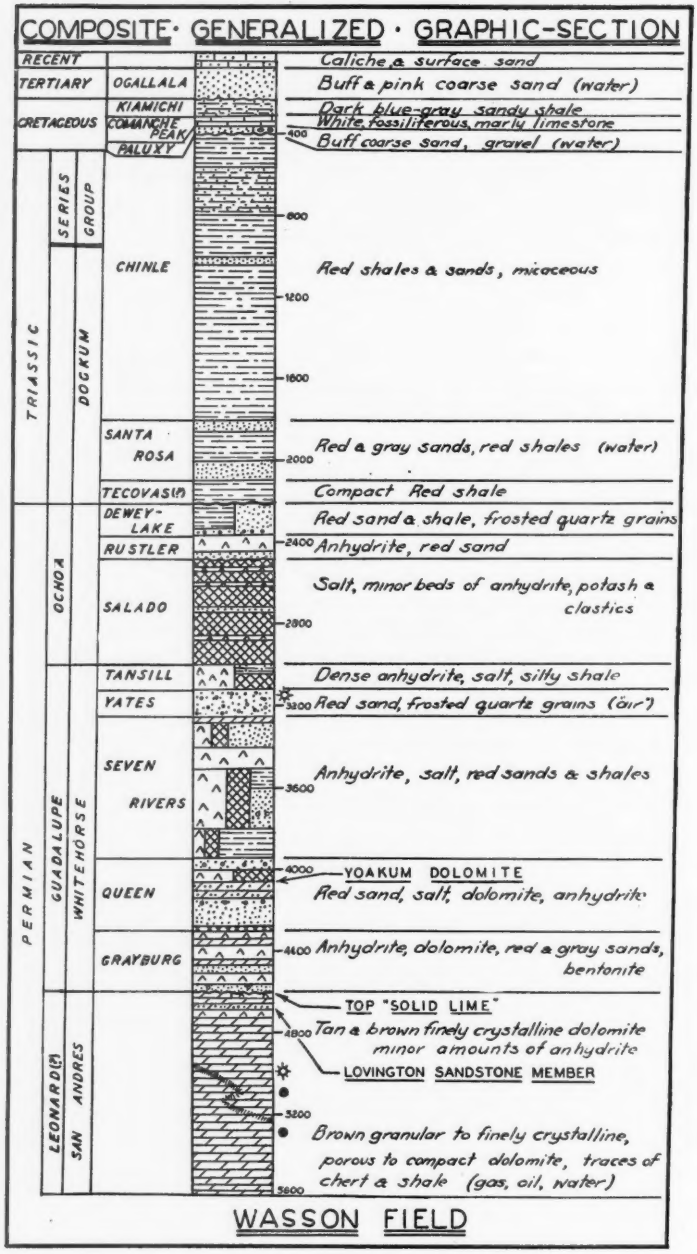

FIG. 4.—Composite generalized stratigraphic section.

CRETACEOUS

Kiamichi, Comanche Peak, Paluxy.—A thin blanket of Lower Cretaceous deposits extends northward over the Llano Estacado from the Edwards Plateau. From the few and mostly obscure data it has been possible to reconstruct a section which agrees with those described at Cedar Lake,[6] Gaines County, and at Guthrie Lake, Lynn County.

The Cretaceous present is divisible into three formations. (1) The Kiamichi, the upper formation, is composed of dark bluish gray shales, sands, and thin limestone members. The total thickness is 50–130 feet. (2) The Comanche Peak (Goodland facies) and Edwards constitute 20–70 feet of crystalline, bedded and fossilliferous limestones with some marly limestones. (3) The Paluxy is a uniform and loose cream-colored sand locally coated with a film of calcium carbonate. The grains are commonly rounded but some samples have been seen in which the sand was composed almost entirely of holohedral quartz crystals. Near the base of the formation some wells have a basal conglomerate or gravel. The thickness of this unit is 0–170 feet.

An average thickness of the Cretaceous deposits can not be determined accurately on account of the lack of data. In Weekly's Knight No. 1 the basal Paluxy is 170 feet thick, but in the Humble Oil Company's Bennett No. 3, Sec. 762, and in A. G. Carter's Moore-Langdon No. 1, Sec. 44, Block AX, Gaines County, the Paluxy is absent. In these wells the Comanche Peak and the Edwards rest on the Triassic redbeds.

The Comanche Peak consists of light-colored marly limestones containing fragments of *Pecten, Exogyra,* and *Gryphaea.* The lower 10 feet of this unit in many places contains a tan granular dolomite which has the aspect of the Edwards limestone present in the plateau province, and with this it has been correlated.[7]

Several fresh-water zones exist in the Cretaceous. The driller's log of the Weekly well records water sands at the following depths: 50–110 feet; 140–188 feet; and at the Cretaceous-Triassic contact from 255 to 265 feet.

TRIASSIC

Chinle formation.—A major unconformity separates the Triassic from the Cretaceous. The upper part of the Chinle formation contains thick red and green coarse sand members intercalated in dark red shales. The iron constituent has assumably been reduced to the ferrous state, giving rise to the characteristic green coloration which mottles the shales and sands in the upper parts of the formation. The upper third of the total 1,400 feet of the Chinle contains more sand, and in the Weekly test a water sand was found at 780 feet. The lower two-thirds is pre-

[6] W. S. Adkins and C. L. Baker, "Geology of Texas," Vol. 1, *Univ. Texas Bull. 3232,* pp. 356–57. Raymond Sidwell, personal communication.

[7] Raymond Sidwell, personal communication.

dominantly shale but has thin beds of sand and fresh-water limestone. One of the latter occurs near the middle of the formation and appears to extend throughout the field.

Santa Rosa formation.—A persistent group of sands known as Santa Rosa is found throughout most of West Texas and New Mexico, and is a uniformly thick sequence over the field. Its three sand members occupy most of the 350 feet of section and are coarse-textured and red-stained except where they contain water. Two of the three sand members are water sands in Weekly's Knight No. 1.

Tecovas.—In several wells a dark red, dense and gel-like shale has been observed below the Santa Rosa sands. It contrasts sharply with the flocculent lighter red shales common to the Triassic and Permian, and it is the writer's opinion that this thin body of shales is the equivalent of the Tecovas shales found elsewhere in the Permian basin. No accurate data can be obtained due to the contamination of the rotary samples. It is estimated that 70 feet of this material is found in the field.

PERMIAN

Dewey Lake formation.—The characteristic fineness of grain consolidation of the sandstone, and the gypsum cement described by J. E. Adams[8] as characteristic of the Dewey Lake formation in the southern part of the basin persist toward the north but possibly with less contrast to the overlying Triassic beds. In many wells the gypsum cement is not to be found and the grain size is nearly like that of the Triassic sands. Aside from the ordinary frosted quartz-grain "horizon" at the base of the formation another has been found close to the top in several of the wells examined. These grains are characteristically larger and more irregular than those below and are in many places accompanied by coarse and angular sands and fine gravels.

Too few data are available to report accurately on the contact of the two systems yet there appears to be some variation in thickness in the Dewey Lake formation within the field. For instance, in the Honolulu-Cascade's Bennett No. 1 the formation was entered at a depth of 2,200 feet and extended downward to 2,420 feet—a thickness of 220 feet, but in Weekly's Knight No. 1 only 100 feet was drilled between 2,040 and 2,140 feet. It is possible that a closer study will show a direct relation between the variation of thickness and structural uplift.

Rustler formation.—In this part of the Permian basin the Rustler anhydrite represents the final espisode of evaporite deposition. It is also the first easily recognizable marker and is commonly referred to as the "top of anhydrite." The unit is 90 feet thick and is divisible into two parts: the upper 60 feet is composed of dense white anhydrite, slightly dolomitic in the south and southwest part of the field; the lower 30 feet contains thin red shale interbedded with anhydrite. The red shale is believed to indicate an unconformity between the Rustler and the

[8] John Emery Adams, "Stratigraphy, Eastern Midland Basin," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 24, No. 1 (January, 1940), pp. 62–63.

underlying Salado. This inference is supported by the fact that the underlying Salado appears to become thinner locally. With reasonable care the contact between the hard Rustler beds and the quickly drilled salt of the Salado formation can be determined by drilling-time data.

Salado formation.—The Salado formation is dominantly halite with thin beds of anhydrite, potash, and very thin beds of red clastic material. As undersaturated mud is normally used in rotary wells, the halite is dissolved; hence, the only reliable information on this unit is derived from the three cable-tool wells.

The greatest variation in thickness of any of the formations penetrated occurs in the Salado formation. The thickness is 550 feet in the Honolulu-Cascade's Bennett No. 1, while in Weekly's Knight No. 1 it is 745 feet or a difference of 195 feet. As shown later the variation in thickness is mappable and is important in the geological history of the field. A persistent thin bed of shaly red sand occurs in the middle of the formation. This sand extends a considerable distance southward from the field and is useful in the correlation of wells. Most of the thin beds of potash salts are confined to the part of the section below this member. The Cowden anhydrite member[9] occurs approximately 150 feet above the base of the formation and is a good marker in sample and drilling-time logs.

WHITEHORSE GROUP

Tansill formation.—The Tansill formation[10] underlies the Salado formation and in the Wasson field is composed of dense anhydrites, red clastics, and halite with an over-all thickness of 125 feet. The upper 40 feet are interbedded anhydrite, red shale, and silt.[11] Bedded anhydrite and salt occupy the lower 85 feet. Sufficient increase in drilling time is usually noted at the top of this unit to signal the proximity of the subjacent Yates sand,—an important fact where high pressure Yates "air" is anticipated.

Yates sand.—Unfortunately the value of the Yates sand as an important marker has diminished greatly because of inadequate means of accurately determining its top. Several factors are responsible: (1) inadequate mud, (2) sample lag not only of the sandstone but an even greater lag of the characteristic spherical frosted quartz grains, and (3) the admixture by lag and recirculation of upper sands. As a result many operators have abandoned the procedure of collecting samples from this part of the section.

The formation is 155 feet thick in the Bennett sector and is composed of a fine-grained red sandstone, in which are included the typical spherical frosted quartz grains, thin beds of anhydrite, salt, and shale. Many of the wells in this

[9] Sam C. Giesey and Frank F. Fulk, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 4 (April, 1941), p. 603.

[10] R. K. DeFord and George D. Riggs, "Tansill Formation, West Texas and Southeastern New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 9 (September, 1941), pp. 1713–28.

[11] It is possible that this 40 feet of anhydrite, red shale, and silt represents the Fletcher anhydrite member of lowermost Salado.—Editorial note.

sector have encountered "air," or more properly a non-inflammable gas with a high nitrogen content. In the area outlined in Figure 8 the gas occurs under abnormally high pressures reaching a maximum of 2,800 pounds per square inch.[12] This gas has been a serious hazard in the drilling of this part of the section and has resulted in the loss of several holes. Showings of gas have been logged in the Yates section in practically all parts of the field but are more prevalent in the east and south parts.

Seven Rivers formation.—The top of the Seven Rivers formation is marked by a very thin bed of porous dolomite equivalent to the so-called "brown lime" at Hobbs and other fields in New Mexico. Below this is a sequence of thinly bedded anhydrite, salt, red shales, and red sands aggregating approximately 700 feet. The upper 150 feet of section is predominantly sand with minor amounts of salt and anhydrite but the remainder contains a larger amount of evaporite material. It is estimated by volume percentage that anhydrite comprises 50 per cent of the total and the remaining 50 per cent is salt, shale, and sand.

The base of the Seven Rivers is marked by red silt and by a basal salt member which contrast with the coarser sands containing abundant frosted quartz grains of the upper Queen formation. This change was found at a depth of 4,035 feet in the Honolulu-Cascade's Bennett No. 1.

Queen formation.—The upper sand member mentioned is correlated with the "Red sand" of Queen age in New Mexico. Dickey[13] states: " . . . the top of the Queen formation is placed at the top of the 'Red sand' of Artesia, a prominent marker as far east as the Texas State line." Though not as prominent a marker in western Texas, the sand does persist into the state and can be readily identified even in rotary samples.

Below the sand member is the 30-foot sandy and porous Yoakum dolomite member described in detail by Fritz and FitzGerald.[14] It lies 140 feet below the top of the Queen. By those who work in the area this member is known as the "brown lime"[15] and is the third marker in the section. The dolomite maintains the character displayed in the Wasson area over much of the north basin area. The sands are in many places dark and give the material a salt-and-pepper aspect. In a few wells in the area of high-pressure Yates gas an additional gas zone has been found in or close to this part of the Queen. Though not as serious as the Yates gas, it aggravates an already serious drilling difficulty.

The remainder of the Queen formation is composed of anhydrite and red

[12] Alden S. Donnelly, "High-Pressure Yates Sand Gas Problem, Wasson Field, Yoakum County, West Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25, No. 10 (October, 1941), p. 1883.

[13] R. I. Dickey, "Geologic Section from Fisher County through Andrews County, Texas, to Eddy County, New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 24, No. 1 (January, 1940), p. 47.

[14] W. C. Fritz and James FitzGerald, Jr., "South-North Cross Section from Pecos County through Ector County, Texas, to Roosevelt County, New Mexico," *ibid.*, p. 25.

[15] How this name was applied to the unit is not understood. The material is neither brown nor limy. Further, it adds confusion to numerous unrelated "brown limes" in the region—particularly with the not-too-distant "brown lime" at the top of the Seven Rivers formation of New Mexico.

sands, containing frosted quartz grains. The base is placed below a salt bed in the few cable tests in or near the field and at the depth of 4,342 feet in the Texas and Pacific's Bennett No. 1. The total thickness of the formation is 330 feet. No evidence has been found indicating other than conformable relations between the Queen and the Seven Rivers above or Grayburg below. However, there is a difference of 50 feet in the top of the Yates sand-Yoakum dolomite interval between the Bennett discovery well and the Weekly well across the field. Most of this anomaly appears to lie in the upper part of the Queen formation, since other correlative units within the Yates and Seven Rivers do not show a variation in thickness.

Grayburg formation.—Of the formations penetrated the Grayburg has the most lithologic variation—a characteristic which is notable over most of the basin. It is here composed of thin beds of dolomite, anhydrite, red clastic rocks and minor amounts of bentonitic shale. The latter, plus the greater percentage of dolomite, differentiate it from the other Whitehorse deposits. Only a few of the dolomite lenses can be traced across the field because few retain their several qualities of texture, color, sand content, or porosity. The thickness of the unit is likewise variable between 300 and 350 feet. Locally the unit thins over the old structurally high areas and regionally a thinning of approximately 5 feet per mile takes place northward to the Slaughter field in Cochran, Hockley, and Terry counties.

The effect of regional gradation within the Grayburg is noticeable in the field. The gradational strike in the Wasson field is northeast-southwest. In the northern sectors of Bennett, Kendrick, and Clawater, the dolomite members are lacking or very thin and the bulk of the material is anhydrite and red clastics. However, southwestward, toward the Roberts, Dowden, and South sectors, the dolomite members thicken at the expense of the anhydrite and red clastics. Fortunately for correlation purposes, the uppermost member, besides being a persistent one in the field, has an earthy texture peculiar to itself. In the Bennett well it was encountered at a depth of 4,415 feet. The first traces of bentonitic shales occur immediately below this member.

Grayburg-San Andres contact.—Unquestionably the most important marker is the so-called "top of solid lime," or top of the San Andres formation. As it is the most conspicuous marker near the pay section, it is used as a basis for mapping the structure. Also it helps to clarify the regional stratigraphic relationship between the San Andres and the Grayburg, which is obscure farther southwest. At the close of San Andres time in this area dolomitic deposition was interrupted on the higher parts of the structure and superseded by clastic and evaporite deposition. The lower parts of the structure continued to receive dolomite deposits in diminishing amounts and the sequence was so gradually disturbed that little indication of the transition is evident. This condition appears to be the source of much confusion in regional correlations, particularly where little control is available. The Wasson field and the Vacuum field of Lea County, New Mexico, fortu-

nately lie within areas of transition and have both types of contacts: abrupt and gradational.

Several writers[16] have indicated an unconformity at the top of the San Andres formation near the edges of the Permian basin. Basinward the degree of unconformity diminishes except where interrupted by local structural movement at or prior to the time of deposition of the superjacent Grayburg. The stratigraphy in the vicinity of the Wasson field appears to conform with that principle. Northward from the field the contact between the San Andres and the Grayburg is extremely sharp with no evidence of gradation between the finely crystalline dolomite of the San Andres and the redbed and evaporite facies of the Grayburg. This might be considered one phase of the unconformity. Southward from the Wasson field in Gaines County, the contact is not so pronounced but passes into a transitional zone. Here the San Andres dolomite, showing the effect of gradation within itself grades upward into the chemical dolomite facies of the Grayburg. The condition here might be considered the second or vanishing phase of the unconformity. By careful examination of well cuttings and close control, the change from one phase to the other can be observed. In the southern sectors, the contact has degenerated to a zone of vertical gradation, 30–40 feet in thickness. Here the tan dolomites of the San Andres grade almost imperceptibly into the densely crystalline dolomites and anhydrites (many of which are sandy and stained red) of the gradational zone and thence into the typically buff-colored and variable dolomites, anhydrites, and sands of the Grayburg. Under these conditions the contact mapped in the northern sectors may be projected southward only with care. Fortunately the Lovington sandy dolomite member described later serves as a key bed by which the contact may be carried through from one end of the field to the other.

SAN ANDRES GROUP

San Andres formation.—The several wells that have penetrated all of the San Andres formation in Yoakum, Cochran, Hockley, and Terry counties, Texas, and Lea County, New Mexico, have had thicknesses ranging from 1,300 to 1,450 feet. Three tests within the Wasson field have penetrated the formation but about two of these tests, A. G. Carter's Wasson No. 4-D and No. 5-D, no geological information is available. The third test, Murchison's Sawyer No. 1, Sec. 702, was found barren in the regular Wasson pay zone and was drilled to 6,850 feet. This well encountered what is considered to be Yeso sand at 6,040 feet. The San Andres top is at 4,590 feet, showing the thickness of the San Andres to be 1,450 feet. Despite the distance between the various tests, the thickness of the San Andres in this well agrees rather closely with: the 1,490 feet penetrated by the Ventura's

[16] Robin Willis, "Preliminary Correlation of the Texas and New Mexico Permian," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 8 (August, 1929), p. 1012.
Robert I. Dickey, *op. cit.*
Lincoln R. Page and John Emery Adams, "Stratigraphy, Eastern Midland Basin, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 24, No. 1 (January, 1940), p. 59.

Lowe No. 1, 14 miles farther west in eastern Lea County; and the Gulf's Mallett No. 4 in northern Terry County which shows a thickness of 1,400 feet.

Within the field the San Andres may be divided into two units, on the basis of texture, color, porosity, and accessory materials. Despite the differences noted the contrast between the two units is not great and they appear to be closely related genetically. No definite demarcation between them has been found; the two units intergrade vertically and laterally. One of the notable features of both units is the lack of clastic materials, and this lack has rendered correlation and interpretation of samples very difficult. In addition, the paucity of clastics with the uniformity of the dolomite gives the section a massive aspect. Generally the structurally lower wells contain more evidence of bedding and contain greater amounts of anhydrite and clastics than the higher wells.

The upper unit is composed of tan to light brown finely crystalline non-porous and uniform dolomites. Thin beds of anhydrite occur, that in general not only decrease in percentage (thickness) on the higher structural positions but also stratigraphically with depth. The only bed of clastic material is found 70–110 feet below the top of the San Andres in the form of sandy dolomite; because of its thinness and persistence it affords good key-bed control in conjunction with the Yoakum dolomite for study of the San Andres-Grayburg contact. This sandy member is correlated with the Lovington sandstone member of the San Andres recently described by Hills.[17] Where best developed, in the Kendrick sector, it consists of 20 feet of finely sandy dolomite and dolomitic sandstone—commonly micaceous and in many places stained pink. An anhydrite bed under the Lovington sand is commonly present in wells on the north end of the field.

As shown in Figures 5 and 6 the interval between the top of the San Andres and the porous dolomite which is considered the top of the lower unit is variable and ranges from 305 feet to 520 feet on or near the structure. Greater intervals are present in the synclinal wells some distance away. The thickening of this interval or thickening of the upper unit is not attributed to structural thickening but to lateral gradation from the porous phase of the lower unit to the non-porous phase of the upper unit.

The lower unit contains oil and gas. Porosity, varying degrees of granular texture, and minor amounts of dark shales and cherts differentiate it from the overlying material. Colors of the lower unit range from buff in the dolomite lentils to the dark browns of the granular oil-saturated material. The black shales are paper-thin partings of little correlating value except locally. Chert is found in several varieties including white chert, granular chert, smooth organic chert with acicular inclusions believed to be sponge spicules and authigenic quartz in crystals and clusters. Its occurrence is erratic and it can be used only as a zonal marker. One zone of organic chert, approximately 650 feet below the top of San Andres, can be found in most of the wells.

[17] John M. Hills, "South Lovington Pool," *New Mexico Bur. Mines and Mineral Resources Bull.* 18, pp. 267–274 (1942).

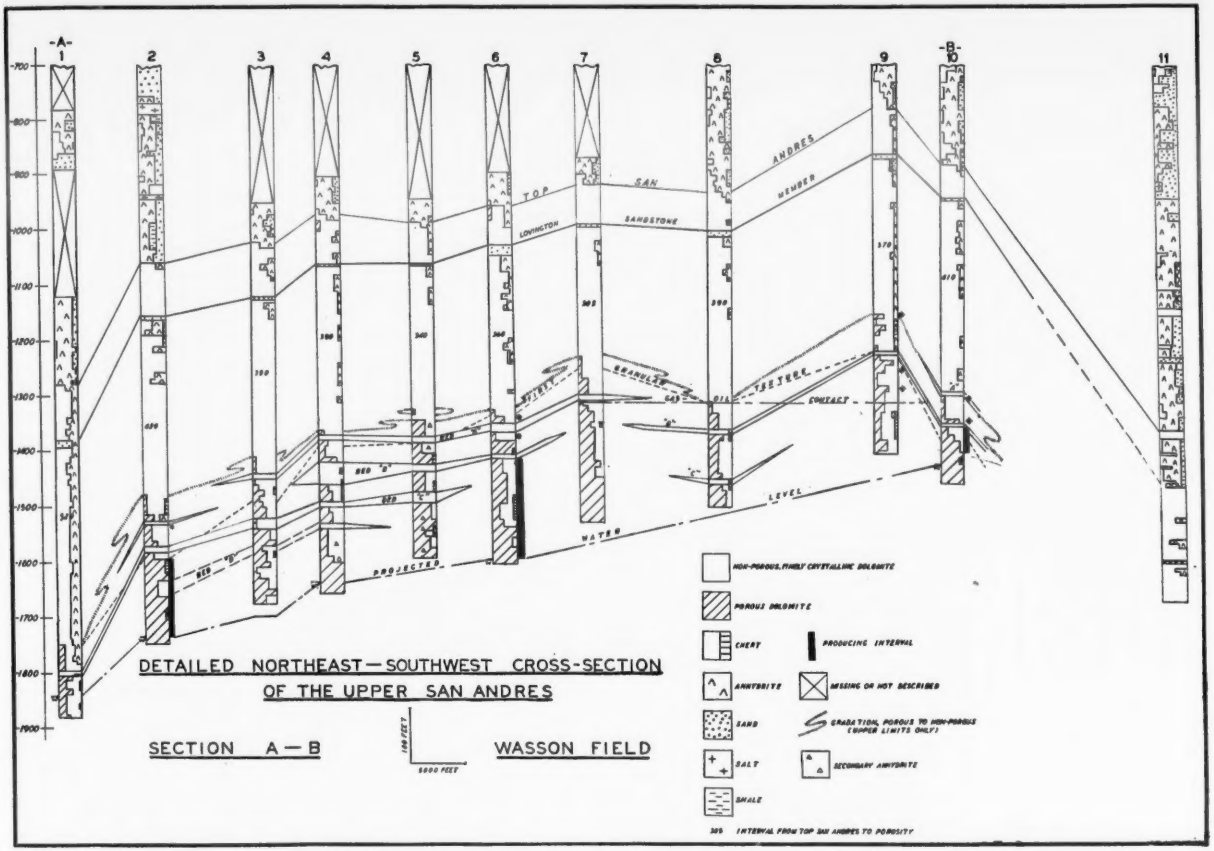

FIG. 5.—Northeast-southwest cross section (*AB*) of upper San Andres, Wasson field.

1. Allison's, D. T. Bush No. 1
2. Texas & Pacific Coal & Oil Co., F. R. Bennett No. 1
3. Devonian Oil Co., W. S. Hodges No. 2
4. Mid-Continent Oil Co., J. G. Comer No. 1
5. Anderson & Pritchard Oil Co., Spearman-Willard No. 3-805
6. Honolulu Oil Corp., R. M. Kendrick No. 1
7. Magnolia Petroleum Co., R. M. Kendrick No. 5-867
8. A. G. Carter & Continental Oil Co., G. M. Langdon No. 5
9. A. G. Carter & Continental Oil Co., A. L. Wasson No. 1-48
10. Amerada Petroleum Corp., F. Matthews No. 1
11. Wahlenmaier-York & Harper, E. H. Jones, No. 1

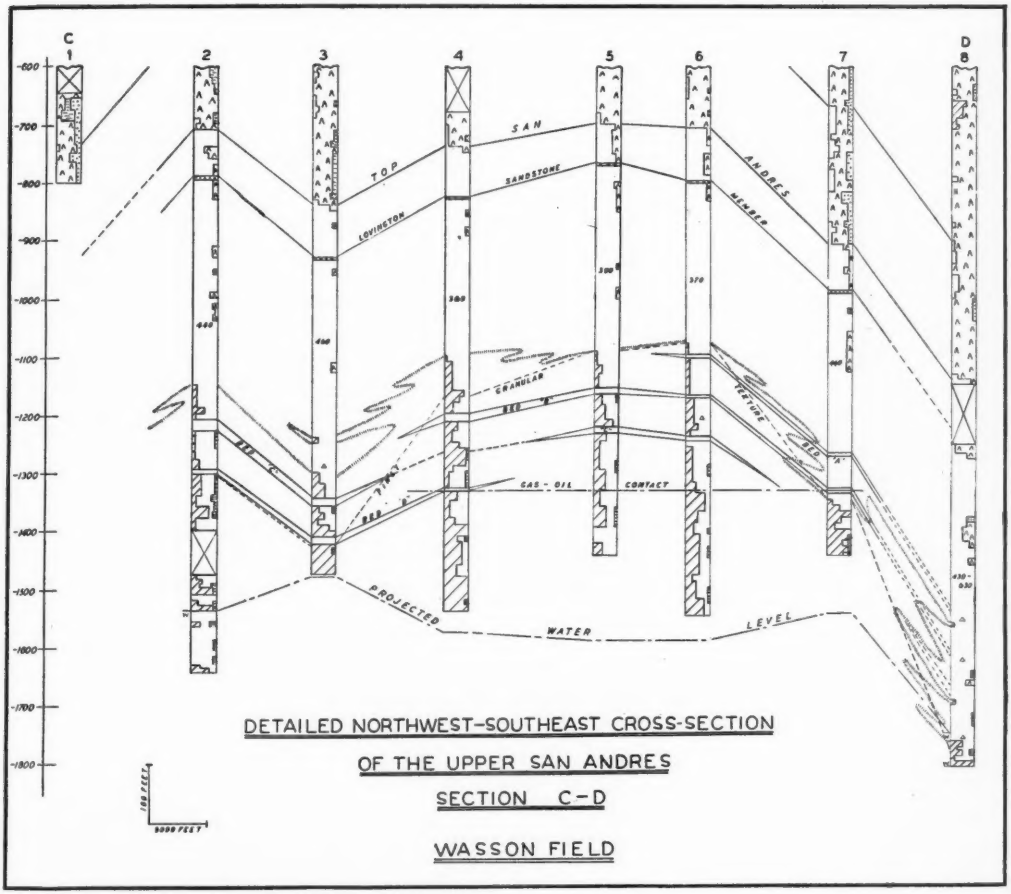

FIG. 6.—Northwest-southeast cross section (*CD*) of upper San Andres, Wasson field.

1. Weekly Oil Co., W. S. Knight No. 1
2. Shell Oil Co., Dora Roberts No. 1
3. Osage Drilling Co., C. A. Hudson No. 1
4. Aloco Oil Co., Pearl Chatterton No. 1
5. Shell Oil Co., C. A. Dowden No. 2
6. Shell Oil Co., E. C. Brand No. 1-A
7. A. G. Carter & Continental Oil Co., G. M. Langdon No. 1-44
8. Shell Oil Co.-Skelly Oil Co., G. N. Robertson No. 1

Fortunately there are within the lower units lentils of dense light-colored dolomite of an opaque semi-crystalline nature that differ from the ordinary finely or granularly crystalline material. Although not ideal markers to follow, they

have afforded valuable control horizons for study of the porous zones and their relation to the structure. These lentils show that (1) the lower unit comforms structurally with the top of the San Andres, at least within the limits of the field; (2) the porous material grades out of the section down-structure, which indicates that the reservoir lies on a depositional "high"; and (3) in three dimensions the occurrence of the porosity and the lentils is sporadic and interfingering locally.

The lentils are designated Beds A, B, C, and D. Bed A is approximately 400 feet below the top of the San Andres, B approximately 450 feet, C approximately 500 feet, and bed D approximately 580 feet. They are best developed in the Baumgart sector and missing to scant along the apex of the northeast-trending fold where the porous dolomite is continuous vertically. The lentils are also difficult to trace in the South sector. In the structurally lower wells on the edges of the field the lentils thicken and additional ones interfinger into the reservoir, making differentiation difficult. Examples are found between the Dowden and Roberts sectors and along the northeast part of the field. Close control is essential throughout the field, to correlate these beds with certainty, because of their similarity in texture and color and because of their proximity. Bed B has the greatest areal extent and is the first prominent lentil encountered in the Baumgart sector, where it is approximately 50 feet below the top of the porosity. Bed A is erratic in occurrence and in the Baumgart sector lies immediately over the porous dolomite. It is the least conspicious of the four. Similar lentils are to be found in the Waples-Platter and Ownby pools northeast of the Wasson field.

Figures 5 and 6 show the manner in which the lentils occur in the reservoir and the relation of the lower beds to the top of the San Andres; also they attempt to show the manner in which the porous material grades into the non-porous. From a study of these sections and the examination of well cuttings the conclusion is reached that an unconformity is not present between the lower and upper units. The change from lower to upper facies is one of vertical as well as lateral gradation; however, the period of transition possibly could be represented elsewhere by a hiatus. In the writer's opinion, the lower facies represents a period of local reef growth on a progressively subsiding but relatively positive area. The upper part of the lower unit that shows the greatest degree of gradation represents the restriction and final stages of bioherm existence in this area. Fossil-cast porosity and small organic residues bear witness to a thriving marine assemblage of organisms even though little other evidence has withstood the effects of dolomitization. As to type, the reef growth can be compared with the lagoonal or atoll growth more common to the San Andres, in contrast to the barrier-type reef of Capitan age in New Mexico. It is interesting to note the similarity between the Wasson reef and the Addu Atoll[18] of the Maldive Group in the Indian Ocean in outline and habit.

Porosity.—One of the most noticeable features of the San Andres in this area is the apparent uniformity of the dolomite and the porosity size. The pores are fine

[18] J. Stanley Gardiner, *Coral Reefs and Atolls*, pp. 17–18. Macmillan and Company, Ltd., London (1931).

and those with diameters greater than 1 mm. are rarely seen in sample cuttings (an estimated average diameter is 0.5 mm. Slightly larger pores are observed in cores but few are larger than 2 mm.). Three forms of porosity have been noted: (1) cavity-type with small irregularly shaped voids; (2) cast-type with pores showing fossil-cast outline and resulting from the removal of organic remains; and (3) intergranular-type porosity in which the interstices are among the dolomite granules of varying degrees of crystallization. The coarser pores are of the cavity and cast types. Under the microscope, pores of these two types appear to be the least permeable and commonly fail to show saturation in an otherwise saturated sample. The intergranular porosity constitutes a large part of the openings and, though finer than the other two, appears to contain the most oil—assumably because of greater permeability. This type of porosity has been noted at levels where fluid increases occurred in cable-tool holes. Many of the finely granular dolomites in the pay section have no visible porosity under a magnification of 40× yet they absorb oil in a sponge-like manner and become saturated unlike the finely crystalline material.

The origin of the porosity, that is, the cause of the reservoir, is a matter of conjecture but some deductions can be made from close examination of the pores. The wall of the fossil-cast pore is a shagreen surface composed of protruding dolomite rhombohedrons, indicating that crystallization followed removal of the organism. The pore linings also show the same degree and type of crystallization as the wall rock and are contiguous. No evidence of calcite or other secondary crystal growth has been found but secondary anhydrite has later filled some of the cavities and preserved the outline of the pore or the organism. Evidence of weathered or cavernous openings has not been identified.

As mentioned previously, the porosity within the dolomite is closely associated with the texture; hence, it is logical to assume that the origin of the porosity was contemporary with and the resultant of the crystallization of the dolomite. Beyond this the problem merges with that of the origin of dolomite.[19]

Traceable zones of secondary anhydrite, though sporadic in occurrence, have been noted between beds A and B and in the absence of these serve to show the stratigraphy. Similar secondary filling is also found between beds C and D on the steeper south and east flanks immediately above the bottom-hole water levels.

YESO-CLEAR FORK GROUP

Samples obtained from Murchison's Sawyer No. 1 show the Yeso-Clear Fork beds to be composed of light-colored and finely crystalline dolomite. Little porosity is present and the section contains more anhydrite than the lower San Andres beds. Since geological information has not been released, at the time of writing, upon A. G. Carter's Wasson No. 4-D and No. 5-D deeper discoveries, the exact

[19] Francis M. Van Tuyl, "New Points on the Origin of Dolomite," *Amer. Jour. Sci.*, Vol. 42 (September, 1916); also "The Origin of Dolomite," *Iowa Geol. Survey Ann. Rept.*, Vol. 25 (1914), pp. 251–422.

nature of the "pay" can not be given but reportedly both are producing from porous granular dolomite similar to the regular Wasson zone. The "Wasson Deep" zone is assumed to be in rocks of Clear Fork age while the Wasson "72" zone is questionably lower Clear Fork or upper Wichita.

STRUCTURE

In many of the Permian oil fields of West Texas and New Mexico an inseparable relationship appears to exist between structure and stratigraphy or structure and lithology. As far as can be ascertained such a relationship existed in the Wasson field in early San Andres time. Furthermore progressive structural movement throughout the later Permian and subsequent time has continued and has accentuated the relation existing between structural position and the lithologic character of the San Andres dolomites.

The present structural attitude of the beds is the result of the cumulative, gentle pre-Tertiary folding plus the regional eastward tilting of the whole region during the Tertiary.

SAN ANDRES STRUCTURE

The present structure is best shown by contouring the "solid lime" or top of the San Andres formation. It is compound, consisting of two dominant lines of folding: one trending N. 30° E., along the east edge of the field (Fig. 7); the other N. 65° W., along the southwest edge. The first-mentioned fold is monoclinal except at its north and south extremities where reverse dips indicate plunging anticlinal folds or noses. The second or northwest-trending fold is anticlinal and has been the focus of greater uplift. It has a relatively steep southwest flank which dips 3°, or equivalent to the dip of the monoclinal fold of the east side. A northward slope from the apex of the structure in Sections 894 and 893 dips more gently, in few places exceeding 1°. When contoured on a smaller contour interval the dip of this slope is not so uniform as shown, but is terraced by gentle northwest-southeast-trending monoclinal folds and small local "highs." The combined effect of the greater structural features give the whole the aspect of an inclined platform with relatively steep southeast and southwest flanks.

Both lines of folding undergo a change in strike near their extremities. The first shifts from N. 30° E. to due north in the Bennett sector, and the second changes from N. 65° W. to N. 40° W. in the Roberts sector. The low structural position of the Osage Drilling Company's Hudson No. 1, Sec. 834, places a structural saddle between the Roberts and Dowden sectors, and it is here that the latter shift in strike occurs. Minor appendant structural features, such as noses and local closures, indicate complementary folding and suggest that the two lines of folding are identical in age.

The maximum closure for the whole structure thus far revealed is 140 feet, all of which is confined to the northwest-trending fold between the −660-foot and

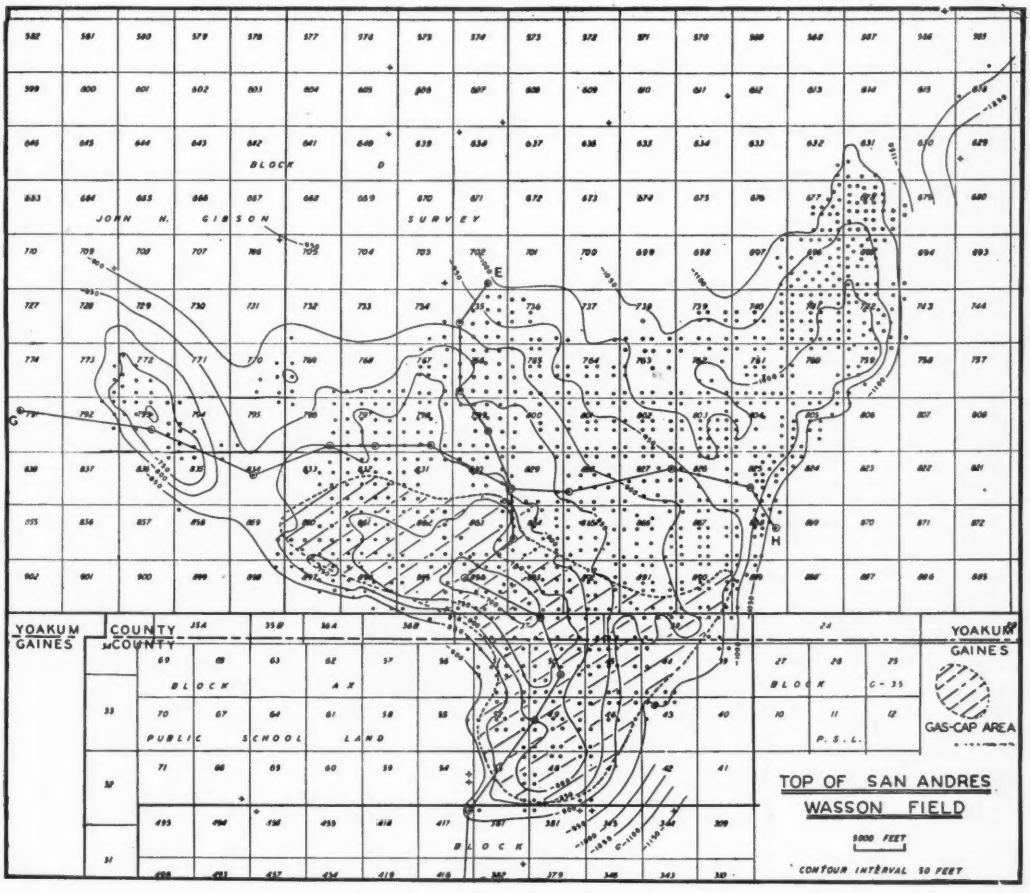

FIG. 7.—Structure-contour map of top of San Andres, showing lines of cross sections *EF* and *GH*.

the −800-foot sub-sea datum. Although Weekly's Knight No. 1, west of the Roberts sector, did not reach the top of the San Andres, its relatively low structural position on the upper markers points to an additional closure of 100 feet. Regardless of closure, a 450-foot differential in the sub-surface elevation of the top of the San Andres exists within the field which is due to the greater uplift of the south end of the field plus the Tertiary tilting.

No evidence of faulting has been found, but irregular convergence and trend of contours in parts of the field suggest the possibility of slumping over deeper faults or irregular warping at the junction of the two lines of folding. Such a con-

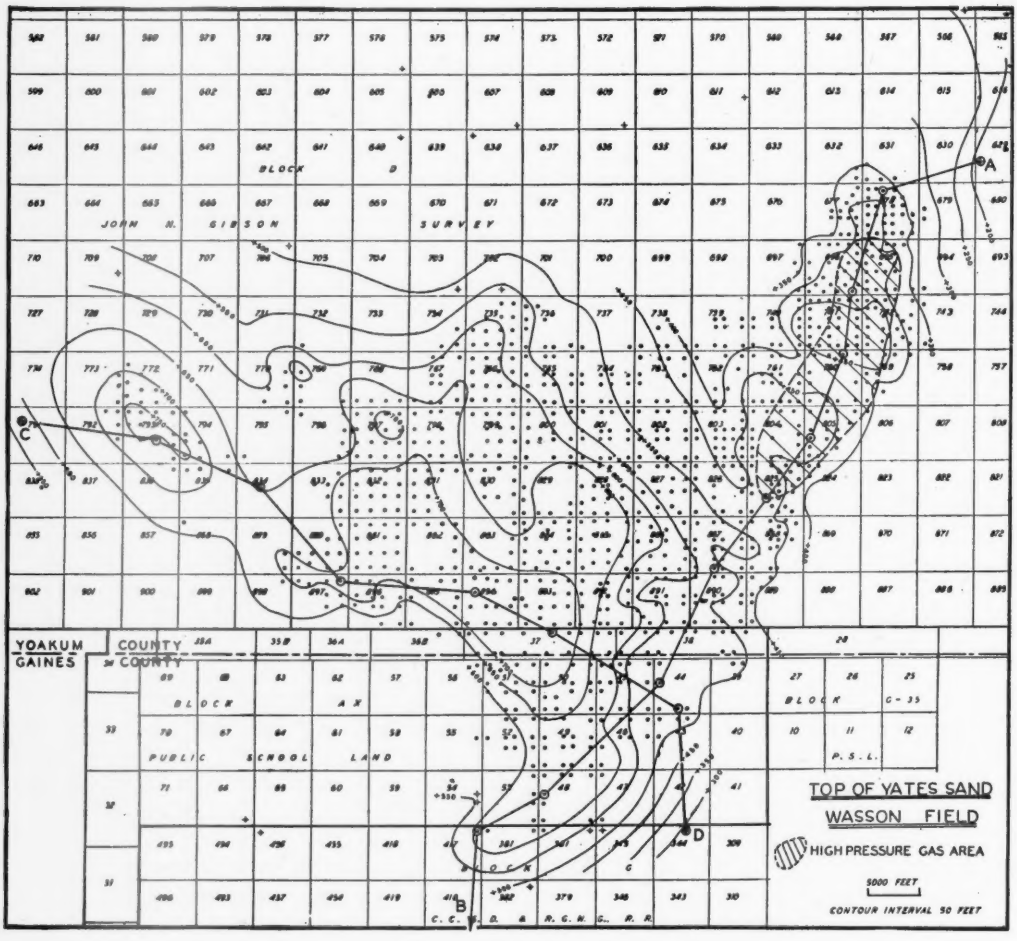

FIG. 8.—Structure-contour map of top of Yates sand, showing lines of cross sections *AB* and *CD*.

dition can be noted in the South sector in Sections 45, 50, 37, and 38 where the contours converge sharply to terminate the northwest-southeast-trending fold.

YATES STRUCTURE

As pointed out frequently by others, the Yates sand formation is an excellent regional marker because of its great extent and its uniform character. In addition, it closely underlies that part of the section which shows the greatest variation in thickness in the upper Permian. Hence, it is normally a valuable aid in determin-

ing the regional and structural history by isopach methods. Unfortunately the data gathered on this formation are the least reliable of those on any of the markers encountered because of the poor recovery of sands and sandstones from uncased rotary-drilled holes. Consequently, many operators do not even collect samples from this part of the section. Drilling time is helpful in determining the top of the formation.

Figure 8 is a map to attempt to show the present structure of the top of the Yates sand. The structure logically follows that of the San Andres in degree and position but where good control is available on the flanks of the structure there is a perceptible decrease in the rate of dip on the Yates sand. The range in elevation is from 700 feet to 300 feet above sea-level, or a relief slightly less than that on the top of the San Andres.

The exact reason for the retention of "air" under abnormally high pressures in the Bennett sector is not known. While showings of "air" are reported over most of the field it is only along the top northeast limb of the structure or the lowest sector of the field that the greatest concentration of gas is found. Presumably the accumulation of gas in this part of the field is primarily controlled by the lithologic character of the Yates sand. Cores taken in the Slaughter field in Cochran County showed the Yates sandstone to be fine and impregnated with salt. The removal of this material by solution in this part of the field could account for a suitable trap for the concentration of gas. The source of this gas is unknown although it has a widespread occurrence over the region.

RUSTLER STRUCTURE

The structure indicated on the San Andres and Yates sand is still discernible on the top of the Rustler formation or "top of anhydrite" regardless of the combined compensating thicknesses of the intervening deposits. The steeper flanking folds noted on lower beds are modified or absent, at least within the present limits of the field.

If it is assumed that the Rustler beds were deposited in a nearly horizontal position, then any structure it now has must be considered as post-Permian in age. This movement is divisible into two parts: post-Permian and pre-Tertiary folding, and eastward Tertiary tilting which is distinguishable on all of the structure maps. The latter movement has tended to minimize local closure by impressing a regional dip upon it. No attempt has been made to subtract this effect or to indicate the pre-Tertiary structure but regional cross sections reveal an average tilting toward the southeast of approximately 30 feet to the mile.

Contours on the top of the Rustler are erratic, as may be seen in Figure 9, and appear to have little relation to the true folding. Similar irregularities were found in the Hobbs field by DeFord and Wahlstrom,[20] who suggest four possible causes:

[20] Ronald K. DeFord and Edwin A. Wahlstrom, "Hobbs Field, Lea County, New Mexico," *Bull. Amer. Assor. Petrol. Geol.*, Vol. 16, No. 1 (January, 1932), p. 60.

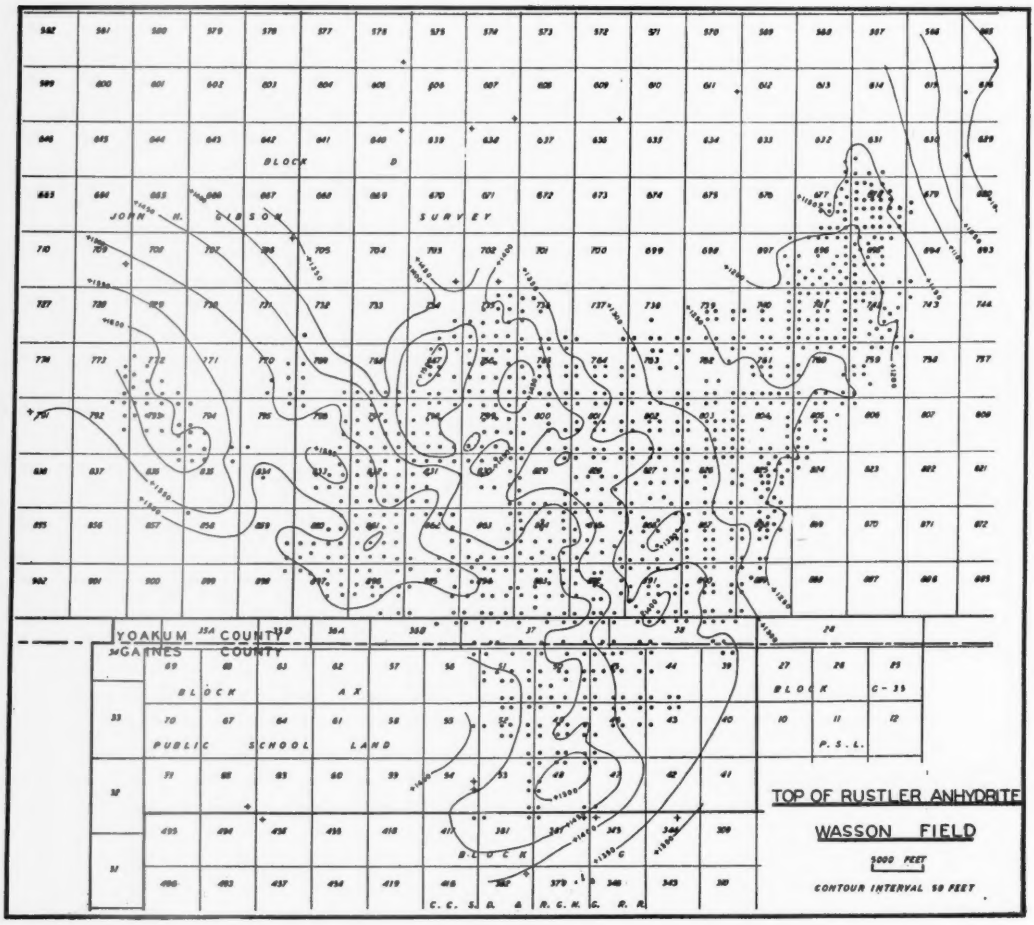

FIG. 9.—Structure-contour map of top of Rustler anhydrite.

(1) inaccurate information, (2) lateral variation in deposition, (3) irregular folding, and (4) slight erosion of anhydrite. Two factors not mentioned, but in the writer's opinion more influential, are the hiatus or possible unconformity between the Salado and the Rustler formations and possible solution and slumping within the Salado salt sections.

Figures 10 and 11 show the relative positions of the various important markers within that part of the Permian drilled.

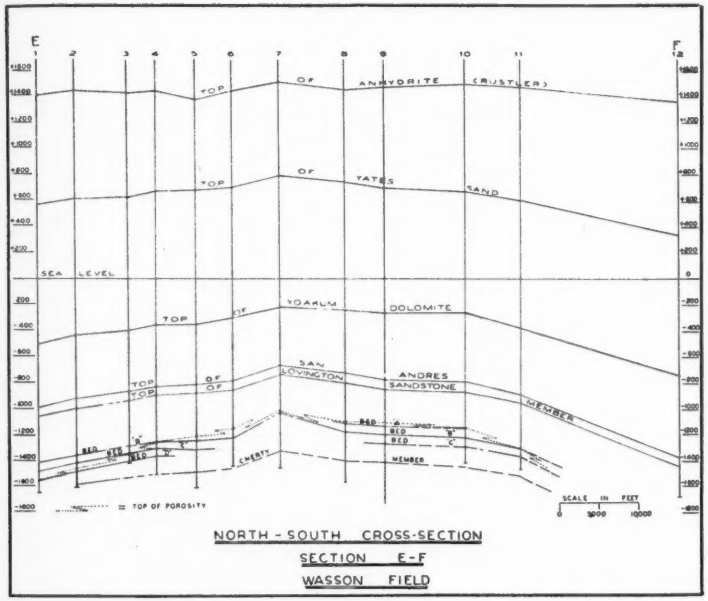

FIG. 10.—North-south cross section *EF*.

1. J. W. Murchison, M. B. Sawyer No. 1
2. Deep Rock Oil Co., W. A. Anderson No. 1
3. T. L. Wynne, L. N. Clawater No. 1
4. Aloco Oil Co., N. W. Willard No. 5
5. Shell Oil Co., Geo. Baumgart No. 6-B
6. T. L. Wynne, C. A. Thomas No. 1
7. Shell Oil Co., C. A. Dowden No. 2
8. Shell Oil Co., E. C. Brand No. 1-A
9. A. G. Carter, A. L. Wasson No. 4-D
10. Continental Oil Co., A. L. Wasson No. 1
11. Amerada Pet. Corp., F. Matthews No. 1
12. Wahlenmaier-York & Harper, E. H. Jones No. 1

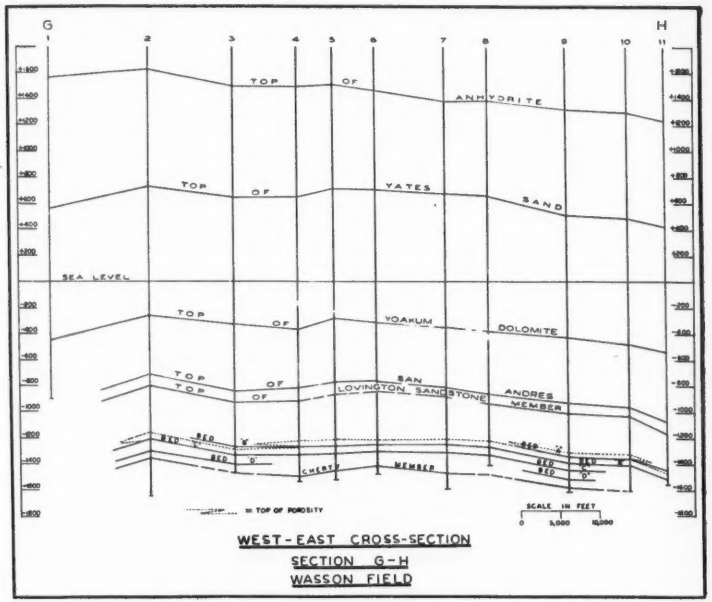

FIG. 11.—West-east cross section *GH*.

1. Weekly Oil Co., W. S. Knight No. 1
2. Shell Oil Co., Dora Roberts No. 1
3. Osage Drilling Co., C. A. Hudson No. 1
4. Gulf Oil Corp., J. C. Futch No. 1
5. Ohio Oil Co., W. Fairman No. 2
6. Humble Oil & Refining Co., J. H. Lynn No. 2
7. Shell Oil Co., Geo. Baumgart No. 6-B
8. Shell Oil Co., Geo. Baumgart No. 1-A
9. Shell Oil Co., Geo. Baumgart No. 9-E
10. Honolulu Oil Corp., R. M. Kendrick No. 1
11. Magnolia Pet. Corp., R. M. Kendrick No. 13

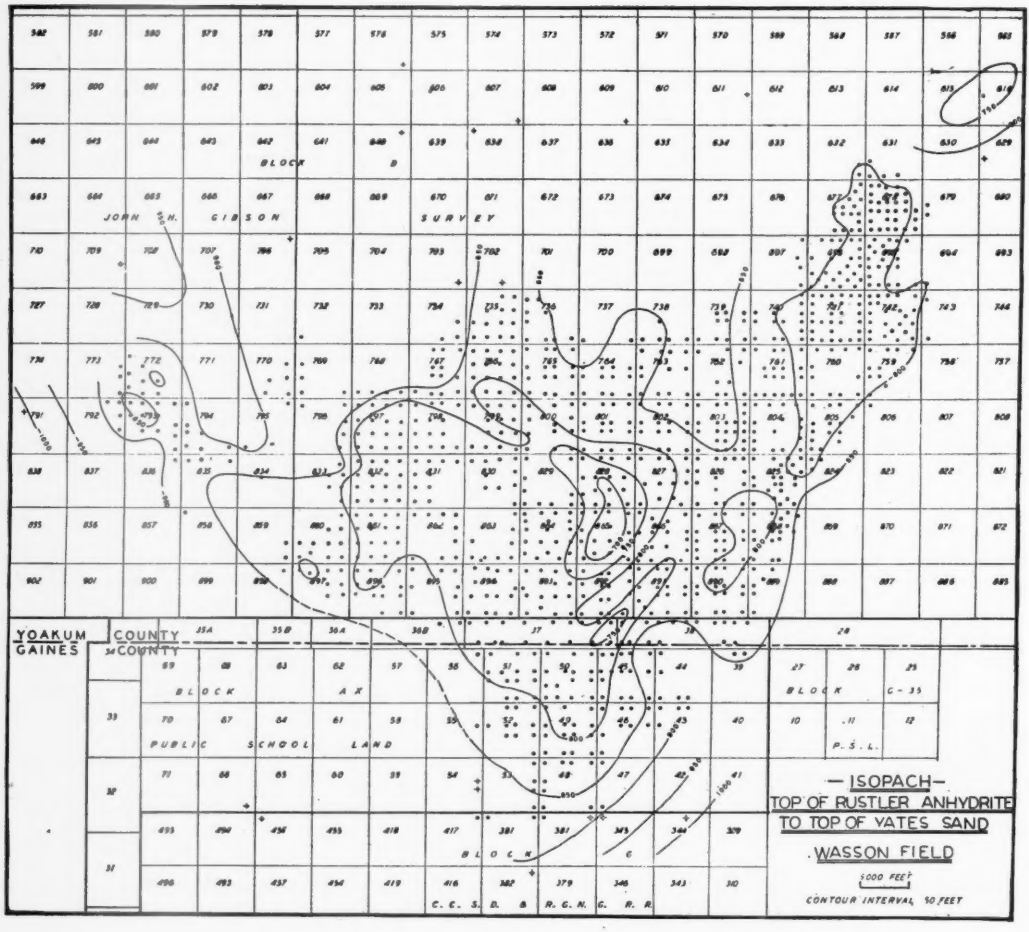

FIG. 12.—Isopach map (top of Rustler anhydrite to top of Yates sand).

STRUCTURAL HISTORY

The known structural movement in the Wasson area has been continuous and progressive from mid-San Andres time until the present. With the exception of the post-Triassic beds each formation or group shows some increment of thinning which contributes to the total structure. However, the progressive westward migration of the structural axes of the field with the relatively strong eastward tilting have masked this effect. Attempts to resolve the total structural move-

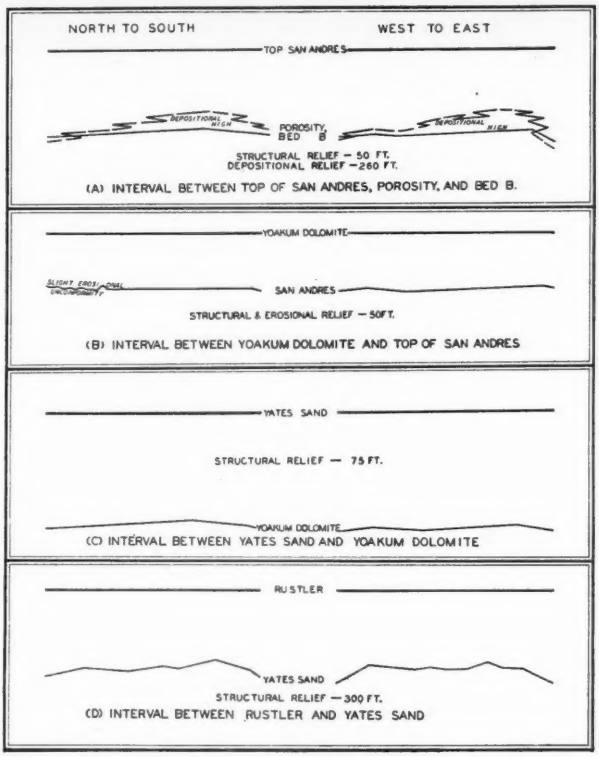
NORTH TO SOUTH
WEST TO EAST
TOP SAN ANDRES
DEPOSITIONAL HIGH
POROSITY, BED B
DEPOSITIONAL HIGH
STRUCTURAL RELIEF — 50 FT.
DEPOSITIONAL RELIEF — 260 FT.
(A) INTERVAL BETWEEN TOP OF SAN ANDRES, POROSITY, AND BED B.
YOAKUM DOLOMITE
SLIGHT EROSIONAL UNCONFORMITY
SAN ANDRES
STRUCTURAL & EROSIONAL RELIEF — 50FT.
(B) INTERVAL BETWEEN YOAKUM DOLOMITE AND TOP OF SAN ANDRES
YATES SAND
STRUCTURAL RELIEF — 75 FT.
YOAKUM DOLOMITE
(C) INTERVAL BETWEEN YATES SAND AND YOAKUM DOLOMITE
RUSTLER
YATES SAND
STRUCTURAL RELIEF — 300 FT.
(D) INTERVAL BETWEEN RUSTLER AND YATES SAND

FIG. 13.—Diagrams to show structural history of elements of movement.

Sector	Well	UPPERMOST POROUS DOLOMITE		UPPERMOST FREE OIL			Sub-Sea Position of Bottom or Edge Water	Total Penetration of the San Andres
		Sub-Sea Datum	Interval to top of San Andres	Sub-Sea Datum	Interval to top of San Andres	Stratigraphic Position (Lentil)		
Bennett	Honolulu-Cascade #1 Bennett Sec. 678. Blk. D.	-1521 ft.	423 ft.	-1528 ft.	430 ft.	B	Approx. -1725 ft.	627 ft.
Bennett	Texas-Pacific #1 Bennett Sec. 678. Blk. D.	-1487 ft.	432 ft.	-1587 ft.	532 ft.	C	-1732 ft.	688 ft.
Kendrick	Honolulu #1 Kendrick Sec. 825. Blk. D.	-1321 ft.	364 ft.	-1420 ft.	463 ft.	B	-1598 ft.	649 ft.
Baumgart	Shell #6-B Baumgart Sec. 829.	-1202 ft.	390 ft.	-1312 (est)	500 ft.	B	-1650 (est)	785 ft.
Clawater	Magnolia #1 Lynn Sec. 770. Blk. D.	-1416 ft.	550 ft.	-1461 ft.	595 ft.	D	-1525 ft.	655 ft.
Clawater	Gulf #1 Elliott Sec. 768. Blk. D.	-1282 ft.	450 ft.	-1389 ft.	557 ft.	Between C & D	-1617 ft.	793 ft.
Denver	Denver #19, Whittenburg Sec. 831. Blk. D.	-1156 ft.	390 ft.	-1336 ft.	560 ft.	C	-1600 (est)	810 ft.
Roberts	Shell #1 Roberts Sec. 793. Blk. D.	-1156 ft.	440 ft.	-1306 ft.	590 ft.	D	-1550 ft.	934 ft.
Roberts	Aloco #1 Walker Sec. 794. Blk. D.	-1254 ft.	430 ft.	-1430 ft.	606 ft.	D	-1521 ft.	700 ft.
Dowden	Shell #1A Brand Sec. 37. Blk. AX.	-1076 ft.	370 ft.	-1351 ft.	645 ft.	D	-1575 (est)	844 ft.
Dowden	Gulf #1 Moore Sec. 897. Blk. D.	-1137 ft.	340 ft.	-1372 ft.	575 ft.	Between C & D	-1525 (est)	690 ft.
South	Carter & Continental #1 Wasson Sec. 48. Blk. AX.	-1151 ft.	367 ft.	Approx. -1351	570 ft.	C	-1450 (est)	629 ft.

FIG. 14.—Chart showing relative depths and stratigraphic position of porosity and fluids.

ment into its component formational increments by isopachs fail because the error in selecting the markers is greater than the change of interval. To illustrate better the structural history the elements of movement have been reduced to the diagrams of Figure 13 where the lines of the sections correspond with those of Figures 5 and 6. In making the sketches the assumption was made that the top or reference bed was deposited in a horizontal manner and that differences in interval were measures of structural movement.

SAN ANDRES MOVEMENT

The structure which existed prior to San Andres deposition is not known. The rather uniform thickness of the San Andres as known from the few widely scattered points in the north basin area indicate that no great structural relief existed. Likewise, there was little movement during the San Andres within the area of the field. As shown in sketch A of Figure 13 the lentil B shows little divergence in dip from that of the horizontal top of the San Andres. Likewise, there is only little discordance in dip between lentils A, B, C, D, and the top of the San Andres in Figures 5 and 6. A nearly constant interval is sustained over the central, southern, and eastern parts of the field but on the north and west and off the steeper flanks approximately 50 feet of thickening is to be found which is interpreted as structural movement. In contrast to this, there is a much greater variance in the interval between the top of "lime" and the first porosity. Here the interval ranges from a minimum of 305 feet on the east side of the field to a maximum of more than 500 feet on the northwest side. This change is accounted for by gradation from porous to non-porous material which gives rise to the depositional "high" located in the south, east, and central part of the field. The apex of this feature appears to have been located between the Kendrick and South sectors. The Magnolia Petroleum Company's Kendrick No. 5, Sec. 867, has the thinnest interval yet observed. The relationship which the depositional feature bears to the earlier structure is yet to be determined but its strike nearly coincides with the present northeast-trending fold.

GRAYBURG-QUEEN MOVEMENT

Only small and uncertain changes in interval occur between the top of the San Andres and the Yoakum dolomite. Thicknesses of sediments between these markers are between the well defined limits of 470 and 510 feet. Attempts to draw isopach maps on this small variation of interval have shown that it is not the result of structural folding but more probably due to a slight unconformity on the top of the San Andres. A maximum structural and erosional relief of 50 feet has been measured for the whole field and is illustrated in sketch B, Figure 13. Any structure which existed at the close of San Andres time was certainly of such small magnitude that it failed to effect the deposition in the shallow brackish seas of Grayburg and lower Queen time. The small regional thickening of the Grayburg toward the south is opposed to that noted in the upper part of the San Andres and is of approximately equal magnitude.

UPPER WHITEHORSE MOVEMENT

The slight positive movement continued through the Queen-Seven Rivers-Yates-Tansill stages. The formations appear to be conformable with no evidence of a large hiatus so that the relief of approximately 75 feet, shown in C of Figure 13, is taken as a fair measure of the movement between the Yoakum dolomite and the Yates sand. Synclinal or "basin" wells located some distance from the field show intervals only 100 feet thicker than the wells high on the structure. The small relief developed during this period of time is characteristic of the north basin area as contrasted with the region on the south.

SALADO-RUSTLER MOVEMENT

The greatest variation in interval found in the section is between the Yates sand and the top of the Rustler formation. Translated into terms of structural movement, it is found that a relief of 200 feet within the present limits of the field was developed by the close of Rustler time and a relief in excess of 300 feet existed between synclinal wells and the highest wells in the field. The unconformity at the base of the Rustler is of regional proportions and probably during that time interval some of the upper Salado salt was removed; however, thin, but persistent beds of anhydrite and sand near the middle of the Salado show that the difference in interval is distributed equally between the upper and lower Salado rather than due wholly to removal of the upper part by erosion.

It is noteworthy that the folding during this interval (Fig. 12) conforms closely with the later post-Permian folding. The crest of the structure was located in Section 865, approximately $1\frac{1}{2}$ miles west of the San Andres depositional "high" in Sections 867 and 891. The high area was still located in the eastern part of the field until after Rustler time. The westward migration of the structure's apex was continued to its present position shown in Figure 9 by post-Permian movement. A similar history of migration is to be found in many of the Central Basin Platform fields and was pointed out by Giesey and Fulk[21] in the North Cowden field.

POST-PERMIAN MOVEMENT

Movement in this area subsequent to the close of the Permian must be grouped into at least two epochs: post-Permian-pre-Cretaceous anticlinal warping and Tertiary tilting. The first can not be specifically dated because of the absence of sufficient sample data on the Triassic-Cretaceous contact; however, the pronounced lithologic change between the Triassic and Cretaceous beds and the presence of coarse basal sands and gravels in the Lower Cretaceous indicate that R. T. Hill's[22] Wichita paleoplain extended as far north as the Wasson field. If the area was peneplaned at this time the present anticlinal attitude of the

[21] Sam C. Giesey and Frank F. Fulk, *op. cit.*, p. 611.

[22] E. H. Sellards, "The Geology of Texas, Vol. 1, Stratigraphy," *Univ. Texas Bull. 3232*, p. 260.

Rustler is a measure of post-Permian folding. Also this folding conformed, and was continuous with, that of the Salado-Rustler stages and attained a relief of at least 250 feet as shown in Figure 9.

The regional Tertiary tilting toward the east has elevated the west part of the field approximately 200 feet higher than the east or about 25 feet to the mile. Because of the character of the reservoir this latter movement to all appearances has had little effect in the accumulation and position of the fluids.

Structural and Stratigraphic Relations of Reservoir

The position of the Wasson reservoir, as well as the relation between the fluids in it, is part of a complex problem which can not be fully solved at present. Structural movement and the structural history have been important factors in the accumulation and position of the fluids, yet stratigraphy, and more specifically the permeability, porosity, and lithologic character of the reservoir rock, have been the dominant controlling factors. In the field as a whole the fluids are not encountered at either a constant sub-sea datum or at the same stratigraphic levels. This is shown in Figures 5, 6, and 14. Locally, where the porosity is uninterrupted laterally and vertically, both oil and water are adjusted by gravity so that the oil-water interface is horizontal. Depending upon the restrictions imposed upon it by the gas cap, lithologic variations, and structural position, the sub-sea depths of the first oil encountered may vary over the field from −1,550 to −1,316 feet.[23] A mean sub-sea datum of −1,330 feet marks the gas-oil contact in the South and Dowden sectors (Fig. 7). Northward the top of the "pay" dips at a slightly greater rate than the structure. The north-edge wells encounter oil at the lowest sub-sea depths ranging from −1,520 to −1,550 feet. Figure 14 shows the position of the fluids in several wells.

The effect of lithologic variations on the control of the fluids can be more clearly shown in the following observations.

1. Oil-bearing porous zones grade laterally into thinner zones of lower order of porosity and finally into non-porous material. This condition is particularly noticeable near the edges of the field where process of gradation and subdivision of pay zones is more abrupt.

2. Fluid records of near-by cable-tool wells indicate that because of lithologic variations fluids do not enter the well bore at equivalent sub-sea or stratigraphic horizons. At a depth of 5,083 feet the Honolulu-Cascade's Bennett No. 1, Sec. 678, filled with 700 feet of oil which increased to 3,700 feet after casing had been run. At an equivalent stratigraphic horizon, 41 feet higher structurally, the Texas and Pacific Oil Company's Bennett No. 1, 2,000 feet west of the first, encountered only a showing of oil but filled rapidly at a depth of 5,150 feet. Similar anomalies are evident in the Gulf Oil Company's Elliott lease in Sec. 768 where 3 cable-tool completions were made.

[23] Most of the wells drilled by cable tools recorded "shows" of oil above the depths given; however, the point at which the first free oil entered the hole was taken as the top of the "pay."

3. Microscopic analysis of well cuttings from different sectors of the field shows that, despite being structurally lower, the eastern half of the field, containing the depositional "high," has more continuous porosity both vertically and laterally, resulting, generally, in greater productivity for wells in this part of the field. The average initial potential for wells in the field on February 1, 1941, was 938 barrels per day[24] whereas most of the well potentials exceeding 2,000 barrels per day occurred in the eastern part. In addition, nearly two-thirds of the field's calculated million-barrel per day potential[25] is derived from the eastern half of the field.

4. A further indication of the gradational process within the reservoir and its effect on the flow and accumulation of fluids is to be found in the confinement of the gas cap. North of the gas-cap area (Fig. 7) porous dolomite is found above the sub-sea level of −1,330 feet yet there is little indication of free gas from the gas cap extending into this zone, and no appreciable oil is found in it. Presumably fluids are not contained therein because of the impermeability and low order of the porosity characteristic of the upper part of the reservoir. This is supported by microscopic analysis which shows the porosity to be of low order and the texture finely crystalline.

5. Finally, the variability of reservoir conditions is apparent in the drilling of wells even on the same lease. Several wells drilled with the same equipment and crews frequently show marked differences in drilling time and the number of rock bits used, which commonly are reflected in the initial gauges of the wells and the sample analyses.

GAS CAP

Of the three fluids present, the free gas is influenced most by structure yet it is not entirely free from lithologic control. The gas cap occupies approximately 12,800 acres of the highest part of the structure, as shown in Figure 7. Its thickness at all points is not known but in the Continental Oil Company and A. G. Carter's A. L. Wasson No. 1, Sec. 48, Blk. AX, the first test drilled in the gas-cap area, the first evidence of excessive gas was encountered at 4,648 feet. Additional showings of gas were logged at 4,675–4,680 feet; 4,693–4,710 feet; 4,840–4,922 feet. The thickness of the gas cap of 230 feet in this well is believed to be near the maximum for the field. On the official potential test this well flowed at the rate of 333 barrels of oil per day plus 6,660,000 cubic feet of gas,—a gas-oil ratio of 20,000 to 1. Other wells have had ratios in excess of 70,000 to 1 before remedial steps were taken.

According to R. S. Anderson and C. G. Cooper[26] the gas-oil contact is not a horizontal interface but is deflected downward under the high part of the South sector and rises near the edges of the gas cap. The meniscus thus formed has a

[24] V. E. Cottingham, personal communication.

[25] Official initial potential gauge is not the result of a 24-hour flow but is calculated by multiplying the second 3-hour flow of a 6-hour test period by 8.

[26] Personal communication.

curvature of approximately 40 feet, varying from a sub-sea depth of approximately −1,310 feet on the edges to nearly −1,350 near the center of the South sector. On the north edge of the cap in Section 863, the Denver Producing Company has set packers at a sub-sea depth of −1,285 feet and reduced the ratios to 700 cubic feet of gas per barrel of oil which is the approximate solution ratio for the field, from the flash liberation method.

North of the main gas cap, in the Baumgart, Denver, and Kendrick sectors, scattered wells have operating gas-oil ratios in excess of 2,000 cubic feet of gas per barrel of crude oil, suggesting that local gas-caps have formed in small closures or stratigraphic traps. Thus far there has not been an excess of gas such as to warrant remedial measures, other than the setting of formation packers, and the operating gas-oil ratios have not exceeded the maximum permissible ratio of 5,000 to 1.

An effort to approximate the total amount of solution gas and free gas produced from the reservoir is made by the North Basin Pools Engineering Committee, pursuant to state-wide orders issued by the Texas Railroad Commission for semi-annual gas-oil ratio surveys. From August, 1938, to December, 1941, nine such surveys were conducted. By multiplying the weighted gas-oil ratio resulting from these surveys by the total crude oil production for the corresponding period, an estimate of the total gas produced is made. Such calculations by the committee indicate that approximately 35½ billion cubic feet of gas had been produced from the reservoir to January 1, 1941.

A gathering system for gas has been installed in the field. On January 1, 1942, 1,013 wells were selling gas to the Shell-Coltexo gasoline plant near Denver City. The capacity of the plant is 30 million cubic feet of gas per day. Residue gas is returned for gas-lift purposes, and for use as fuel. The large number of wells connected to the gas system and the disposal of the residue gas have given the field an efficient means of gas disposal not available to many other West Texas fields.

An analysis of typical Wasson casinghead gas, from the Honolulu Oil Corporation's R. Bennett No. 5–677, Sec. 677, Block D, J. H. Gibson Survey, follows.

	Percentage
Methane	6.2
Ethane	86.7
Oxygen	0
Nitrogen	7.1

B.T.U. per cu. ft. at 30 inches of pressure and 60°F.: 1589
B.T.U. per cu. ft. at 14.4 inches plus 8 ounces at 60°F.: 1610
Hydrogen sulphide: 420 grains per 100 cu. ft.

BOTTOM-HOLE WATER

The exact relation between the oil and water in the Wasson reservoir is not known. The problem is complex and data are insufficient and approximate. Several interpretations exist regarding the occurrence of the bottom-hole water; yet, in

its broader aspect, and irrespective of interpretation, the upper water surface is concave or bowl-shaped, inverse to the structure. Comparison of Figures 15 and 7 show that water is generally encountered stratigraphically higher near the edges of the field where the loss of structural position is greatest. Assumably the peripheral water rises stratigraphically until checked by an impervious "shell" and then descends with the structure into synclinal areas beyond the field. This procedure is illustrated by the reversal of the water contours on the southeast flank of the field and the inverse relation to the structure on the southwest flank.

A specific example of the habit of the water near the edge of the field is found in the South sector. Wells located on the structurally high part of the sector in Section 49 do not encounter bottom-hole water above a sub-sea depth of −1,500 feet, but on the extreme south edge of the field A. G. Carter's J. R. Sharp No. 2, in the southwest corner of Sec. 47, logged water at a datum of −1,445 feet. Its southwest offset, an abandoned well in Sec. 380, reported water at a sub-sea depth of −1,428 feet, and 1½ miles east, a stucturally low and dry test, the Shell Oil Company and the Skelly Oil Company's G. N. Robertson No. 1, Sec. 344, found sulphur water at a sub-sea depth of −1,749 feet.

Another feature of the apparent water level is the downward slope toward the northeast in the manner of a tilted bowl. The rapid rise in the section of the apparent water level on the southwest flank of the field is inverse to the structure, as mentioned; therefore, it can not be considered as "stratigraphic water." On the northeast, along the east edge of the field, as shown by Figure 5, there is very little discordance of dip between the bottom-hole water level and the dip of the stratigraphic units; hence, the water is considered "stratigraphic." Except very locally, this section along the east edge of the field is the only part where a consistent stratigraphic equivalency of the bottom-hole water has been found. On the whole, the water level is confined neither to a common sub-sea depth nor a common stratigraphic level.

Several factors that must be considered in analyzing the bottom-hole water data render the problem incomplete. (1) Fewer than 10 per cent of the total wells drilled have encountered bottom-hole water. Most of the data come from the edge wells where structural position is least favorable. Very few wells in the central area have encountered water despite a greater penetration by several hundred feet. In the contouring of Figure 15 total depth data of wells not finding water were used as a guide to determine at least the upper limit of the water. (2) The practice of drilling-in with rotary tools, though more economical, has reduced the accuracy of locating the position of bottom-hole water. (3) Some wells have been acidized into bottom-hole water; in others, acid waters have intermingled with formation water to give confusing analyses. (4) Intermediate or "pocket" waters have been reported and can seldom be accurately located; these add confusion to the interpretation. In some wells such waters have been exhausted while in others they have not.

Experience in the development of the field has shown that the exact prediction

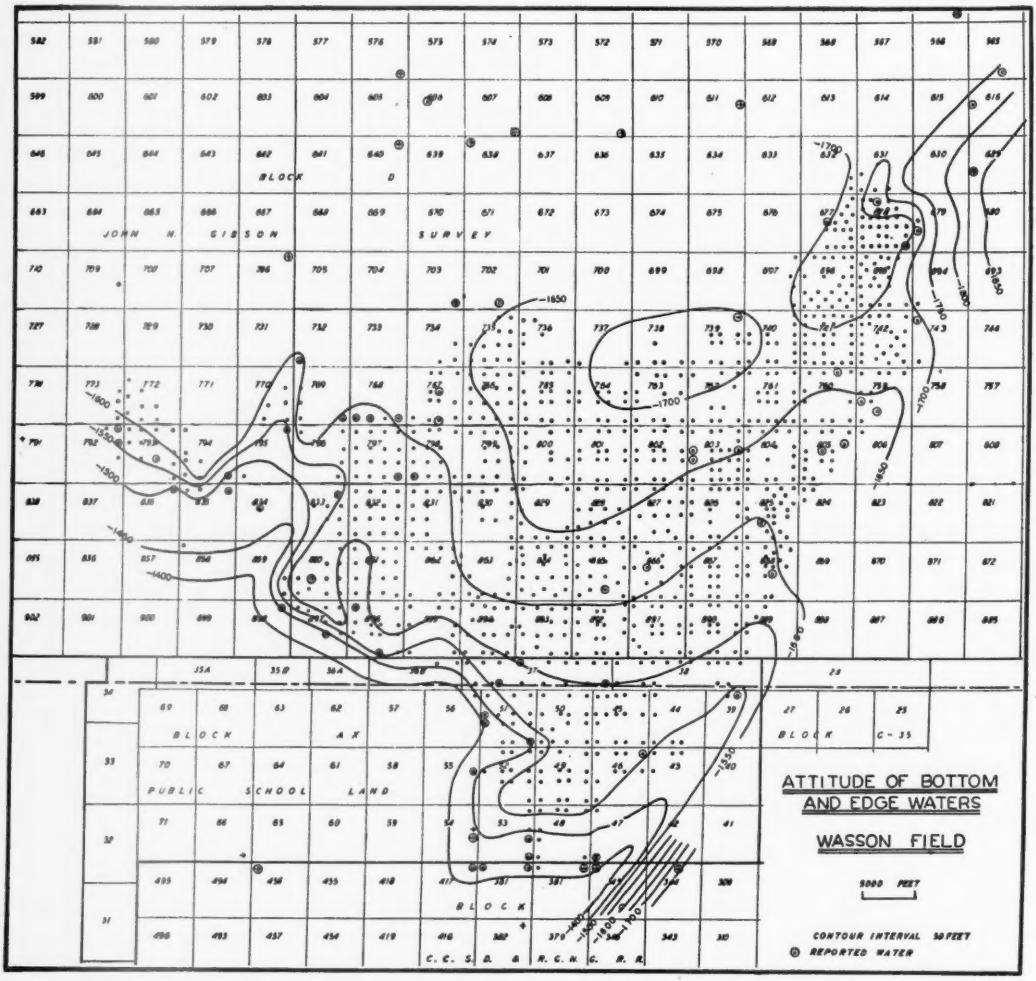

FIG. 15.—Attitude of bottom and edge waters.

of the position of bottom-hole water is hazardous because it is non-conformable with stratigraphic or sub-sea levels. Therefore, as a practical guide, the map serves only to approximate the position of the bottom-hole water and to fix the upper limits on the basis of data thus far obtained.

Two interpretations may be applied to the water data. Either or both may ultimately satisfy the contours as set forth in Figure 15.

First, a single oil-water interface exists which lies in the position shown by the

contours. In this interpretation the first waters would be considered essentially equivalent. The apparent lack, generally, of stratigraphic or gravitational control suggests that another force peculiar to the reservoir is responsible. By comparison the concave surface of the oil-water contact corresponds with the gas-oil meniscus described previously. Both surfaces are deflected downward under the areas of the higher bottom-hole pressures and conversely the areas of low bottom-hole pressure are areas of higher bottom-hole water. The cause of such a disposition of fluids in the reservoir can not be definitely known until correlations are made between bottom-hole pressures and permeability measurements taken through the whole of the reservoir. Furthermore, since the predominant type of energy affecting the reservoir is not yet known, no final statement can be made about its bearing upon the position of the fluids in the reservoir.

The effect of stratigraphy on the position of the water must also be considered. As previously pointed out with regard to a section along the east side of the field (A-B, Fig. 5), the bottom-hole water appears to conform with the dip of the lentils. Sections parallel with A-B do not show the stratigraphic alignment of the waters, yet there is a similar and general northeastward dip across the structure. It is probable, therefore, that the position of the water is influenced by the partly bedded material and is in a sense stratigraphic.

Some geologists regard the progressively higher water level from north to south as the result of a regional tilting of such recent time that fluids have not had sufficient time to be adjusted to the normal sub-sea position. Such reasoning does not account for the greater rise of the water level on the southwest flank where no indication of tilting is evident. Furthermore the Tertiary tilting from the west described previously has had no obvious effect on the position of the fluids. The focal point of vertical movement is in the Dowden sector and is asymmetrically located with respect to the whole field. This results in a steep southwest flank and a more gentle and extensive north flank, giving the impression of a tilting of the whole region, though actually only the area north of the focus is involved.

The second interpretation is based on the assumption that bottom and edge waters interfinger into the flanks of the structure along the more permeable zones. To confirm or disprove this interpretation, additional water data are necessary and the close observation of water encroachment or replacement is essential. It is noteworthy that if waters interfinger into the reservoir at progressively higher levels around the edge of the structure, they have only small penetration into the fields, for many of the wells offsetting those in which bottom or edge water has been found are free of water. A typical example of the possible short penetration is found near the center of Sec. 51, Block AX, Gaines County, where the Continental Oil Company's Wasson No. 6–51 was reported[27] to have flowed 14 barrels of oil and 130 barrels of water at a total depth of 5,080 feet, and it was necessary

[27] V. E. Cottingham, "General Statistical Report Covering the Wasson Field, Gaines & Yoakum Counties, Texas, February 1, 1941," p. 207.

to plug back to a depth of 4,976 feet to eliminate the water. This sub-sea depth of −1,398 feet is approximately 40 feet above the depths of near-by wells and 100 feet above wells in the north part of the same section. Another objection to this interpretation is that intermediate packers have not succeeded in disclosing oil below water levels but bottom-hole packers or plugs have been successful in shutting off water. Should the second interpretation be proved correct, the contours, as shown in Figure 15, would represent the envelope of a group of water points taken from different stratigraphic levels.

Chemical analyses of waters over the field are similar, yet there is a progressive increase in the total solids in solution from south to north. Two water analyses from opposite sides of the field are typical of the range in chemical composition.

WATER ANALYSIS NO. 1

Shell Oil Company's R. A. Cox No. 1, Sec. 380, Block AX, P.S.L. Depth: 4,995 feet, sub-sea −1,456 feet.

Constituent	*Parts Per Million*	*Percentage by Analysis*	*Reacting Value Percentage*
Na	19,363	27.89	34.96
Ca	4,080	5.87	8.48
Mg	1,920	2.76	6.56
Cl	39,600	57.06	46.38
SO_4	3,220	4.65	2.79
HCO_3	1,220	1.76	0.83
Total solids	69,403	100.00	100.00
H_2S, trace			

WATER ANALYSIS NO. 2

Honolulu Oil Corporation's F. R. Bennett No. 5-678, 2,200 feet from the north line and 1,326 feet from the east lines of Sec. 678, Block D, J. H. Gibson Survey. Depth: 5,262 feet, sub-sea −1,716 feet.

Constituent	*Parts Per Million*	*Percentage by Analysis*	*Reacting Value Percentage*
Na	53,676	34.33	43.16
Ca	3,541	2.27	3.29
Mg	2,338	1.51	3.55
Cl	92,800	59.34	48.41
SO_4	3,644	2.34	1.41
HCO_3	305	0.21	0.18
	156,420	100.00	100.00

BOTTOM-HOLE PRESSURES

Six bottom-hole-pressure surveys were made in the Wasson field by the North Basin Pools Engineering Committee from its inception in April, 1939, through December, 1941.

Semi-annual surveys have been made at variable calendar periods to expedite the considerable task of surveying not only the Wasson field but the Slaughter and Seminole fields, also in the committee's charge. An orderly but rapid drilling campaign took place within the period covered by the first four surveys, resulting in many local inconsistencies and unstable conditions within the reservoir with

corresponding fluctuations in the bottom-hole pressures. A compilation of these surveys by the committee[28] follows.

Survey	*Month and Year*	*Number of Wells*	*Arithmetical Average P.S.I.*
First	April–June, 1939	197	1,623.81
Second	Oct.–Dec., 1939	591	1,636.93
Third	May–Sept., 1940	851	1,663.89
Fourth	Oct.–Dec., 1940	1,031	1,666.78
Fifth	May–July, 1941	1,070	1,677.65
Sixth	Sept.–Nov., 1941	1,269	1,663.25

The original maximum bottom-hole pressure of the reservoir is estimated to have been approximately 1800 p.s.i. Several small areas, shown in Figure 16, have maintained pressures near the estimated original pressure. The first survey was made 3 years after the Bennett discovery and nearly 2 years after the South and Denver discoveries. At the time of the first survey approximately 5 million barrels of crude had been removed from the reservoir by wells widely scattered in the whole area. The first surveys of 1939 almost completely outlined the subsequent pressure pattern of Figure 16. Low-pressure areas were found along the structurally steeper flanks and lower parts of the structure where high bottom-hole waters limited the depths of wells to the upper less porous and less permeable zones. Pronounced low-pressure re-entrant areas were found in Sections 834, 768, 769, and the north part of 763 on the north side of the field. Most of the wells requiring secondary methods of recovery are grouped in these areas and their pressures were obtained by use of echometer soundings. Comparison of the structural pattern with that of the bottom-hole pressures shows a normally direct relation. However, wells favorably located on the structure, sufficiently deep, and located within pressure "lows" are commonly found to have less effective porosity than adjacent wells. As mentioned previously, these wells commonly show slower drilling time and more bits are used in drilling-in. In the Bennett sector the bottom-hole pressures decrease northward in a similar manner to the structural contours. On the steep southeast and southwest flanks the decline in pressure is first noticed well down on the structural flanks on account of better developed effective porosity on these flanks.

The arithmetical average of the bottom-hole pressures increased in succeeding surveys and reached a maximum in the fifth survey. At the time of the earlier surveys much of the undeveloped area within the proved limits of the field lay within the 1,700-pound contour of Figure 16. As a result, subsequent bottom-hole-pressure averages were higher. In addition, many wells in the central part of the field were deepened after it was learned that additional penetration could be made without encountering bottom-hole water. In some wells the deepening not only increased pressures in that well but resulted in higher pressures in near-by shallower wells. Pressure adjustments such as these support conclusions reached

[28] North Basin Pools Engineering Committee, V. E. Cottingham, chairman, "General Statistical Report Covering the Wasson Field, Gaines and Yoakum Counties" (February 1, 1942). Available only to members of the committee.

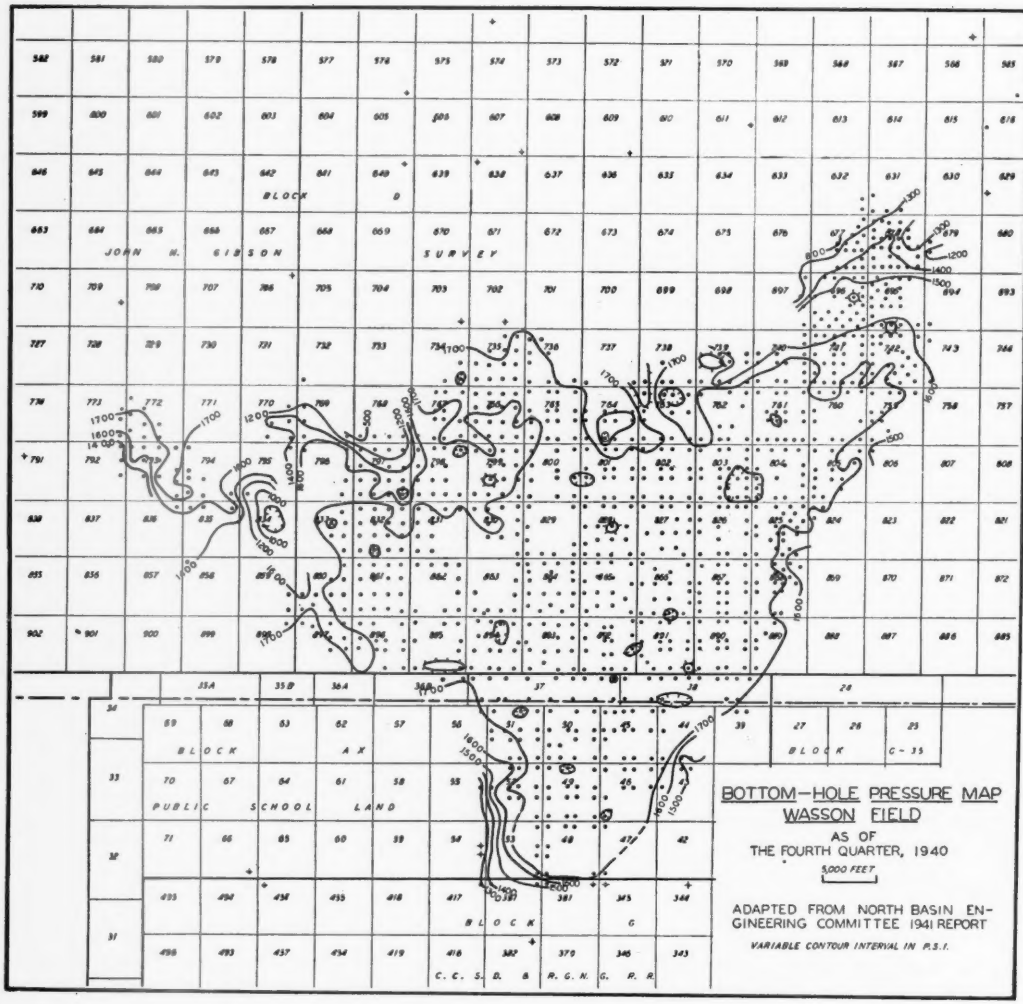

FIG. 16.—Bottom-hole pressure map.

by microscopic analyses that the dense lentils of dolomite are sufficiently impermeable in parts of the reservoir to prevent vertical movement of fluids. Since the lentils are not everywhere present, similar equalizations of pressure might be expected over a greater period of time through more devious channels.

Exploitation has diminished to the point where the reservoir can be considered

stabilized. Pressure surveys on identical wells for the last three periods shown above reveal the average bottom-hole pressures on 795, 927 and 1,070 wells to be 1,675, 1,678, and 1,682 p.s.i.,[29] respectively. It will be noted that the sixth survey average is near the mean of the fourth and fifth surveys. Individual pressure fluctuations have reduced to less than 20 p.s.i. over most of the area of higher pressure yet considerable variations still exist in the low-pressure areas where lower permeabilities assumably resist equalization of pressure.

Pressures are taken after wells have been shut in at least 48 hours, but not longer than 60 hours, as prescribed by the field rules, and are corrected to a subsea datum of −1,350 feet.

The predominant energizing force of the reservoir is not definitely known. In the early development stages of many West Texas fields it is difficult to forecast the type of "drive" present—in this respect the Wasson reservoir is representative. Weighted gas-oil ratios determined from nine periodic field surveys from October, 1938, to December, 1941, show a decrease from 1,148 to 965 cubic feet of gas per barrel of oil. These periodic weighted gas-oil ratios were determined by dividing the total oil produced into the total gas produced for each survey. However, the first of these surveys were made on only 132 wells while the last was for 1,301 wells. From December, 1940, to December, 1941, the weighted gas-oil ratio decreased from 1,137 to 965 cubic feet of gas per barrel of oil. Part of this field decrease was due to low gas-oil ratios in new wells drilled around the margin of the field being added to the total, and part to remedial work on high gas-oil ratio wells. Individual wells and the field as a whole have shown considerable variation in ratios during the several surveys.

Evidence of water-drive in terms of water encroachment is even less apparent at present than gas-drive. To the writer's knowledge, few if any wells are making water which had not originally reported it upon completion. Several operators have reported relatively small increases in the percentage of water cut while others have reported no change or exhaustion of water. From the data available, edge waters do not appear to be responsible for the existing bottom-hole pressure for the following reasons: (1) none of the edge producers or abandoned wells which encountered water has had a hydrostatic head of water comparable with reservoir pressure; (2) the manner in which the porous dolomite grades into nonporous material off the flanks of the structure does not permit large bodies of water to invade the upper edges of the reservoir. The lower part of the San Andres, as revealed by several wells in the surrounding area, is very porous which suggests a possible entry into the reservoir for a water-drive.

Exploitation

Engineering Committee

Through the coöperation of most of the operators, of which there were fifty, on July 1, 1942, operating 245 leases in the Wasson field, the North Basin Engi-

[29] V. E. Cottingham, *op. cit.*

neering Committee was organized and commenced operation on March 1, 1939, under the chairmanship of V. E. Cottingham. Its function has been to make physical surveys of the reservoir and compile engineering data for the Wasson, Seminole, and Slaughter fields. As a result of the committee's work the field has been judiciously and efficiently exploited.

FIELD RULES

Field rules, regulating exploitation, were proposed by operators and received the sanction of the Texas Railroad Commission. Some of the more pertinent rules follow.

Well-spacing for the regular Wasson or 5,100-foot "pay" is based on a 20-acre unit plan with the restriction that the unit's length can not exceed twice its average width. A further restriction is made whereby wells can not be located closer than 330 feet to a lease line or 770 feet to any other producer on the same lease. Spacing rules adopted in June, 1941, for the "Wasson Deep" or 6,200-foot pay zone, have provided for acreage units of 80 acres, with wells located not closer than 660 feet from lease lines and 1,700 feet from another 6,200-foot well or within 100 feet of a well producing from the regular zone. Field rules have not been adopted for the third "pay" or 7,200-foot zone—termed "Wasson 72."

Although a density of 20 acres has been adopted as the unit density, operators have the option of assigning a contiguous 40-acre unit, whose length is not more than twice its average width, to one well and thereby increasing the portion of the well's allowable based on acreage. Most of the leases have been developed in this manner and wells are located 330 feet, 440 feet, or 660 feet from the lines of the 40-acre tract.

Individual well allowables are determined by prorating the field's allowable among the total number of wells on the basis of 50 per cent allotted to the assigned acreage and 50 per cent allotted to the potential. Thus, a well drilled on a 40-acre unit receives $33\frac{1}{3}$ per cent more allowable than one drilled on a 20-acre unit, provided the initial potentials are the same. This formula was adopted when the original Wasson area, with its 40-acre spacing and proration units and the Bennett area, with its 20-acre spacing and proration units, were known to be a common reservoir. Penalties are provided against wells with gas-oil ratios in excess of 5,000 cubic feet of gas per barrel of oil.

Initial potentials of wells are calculated to a 24-hour basis by multiplying by 8 the flow of the last 3 hours of a 6-hour test and are witnessed by the engineers of the engineering committee. This test must be through tubing of a diameter not larger than $2\frac{1}{2}$ inches. The operator may elect the size choke to be used during a potential test but it must remain constant throughout the test except in gas-lift tests, which are limited to a potential of 400 barrels per day. Beginning January 1, 1942, the potential production of each well will be adjusted annually according to the bottom-hole pressure fluctuations by the following adjustment formula:

$$\text{New potential} = \frac{\text{Existing potential} \times \text{Reservoir datum pressure at correction date}}{\text{Reservoir datum pressure of last annual observation.}}$$

DRILLING METHODS

Rotary tools have been used predominantly in drilling the wells. With the exception of the first two wells in the field, all wells have had the section above the top of the San Andres drilled by rotary methods. In the earlier stages of the development of the field several operators chose to drill in with cable tools where excessive gas was not present. Standardization was made at various depths within the San Andres above the oil zone.

Normally two strings of casing are set: a surface string ranging in size from $8\frac{5}{8}$-inch to 13-inch; and an oil string of $4\frac{1}{2}$-inch, $5\frac{1}{2}$-inch or 7-inch, but in the high-pressure Yates sand gas area[30] an intermediate string of casing of $9\frac{5}{8}$-inch or $7\frac{5}{8}$-inch is set in the Rustler anhydrite or in the Tansill formation above the Yates sand. Field rules require that the surface casing be set at a depth of at least 150 feet or at least 25 feet into the redbeds, the annular space behind the casing to be solidly cemented to the surface, as protection for the potable waters of the Tertiary and Cretaceous beds.

The redbeds are drilled with drag and rock bits, but upon entering the Rustler anhydrite rock bits are used for the remainder of the hole.

Most operators do not use commercial muds in drilling the redbed section but utilize the natural mud from the red shales, which is generally of inferior quality. Native clays or commercial muds are added in varying amounts from the top of the Rustler to the oil-string casing seat. Too frequently few precautions have been taken to condition the mud correctly and sample returns have been of poor quality. Some operators have dissolved crushed salt in the mud just prior to drilling the salt section to prevent solution cavities. This procedure has been beneficial in eliminating much of the whip of the drill pipe and has yielded excellent upper-hole samples. One of the noteworthy results of the use of saturated drilling brine, when conditioned with bentonite treated to be used with salt water, is the excellent manner in which it returns sands and sandstone cuttings—as a result very good Yates sand correlations have been obtained from the wells in which this procedure was followed.

The depths at which the oil string of casing has been set varies with the structural position of the well, the location of the gas-oil contact, and the policy of the operator. The usual range of oil-string lengths is from 4,500 feet to 5,000 feet where casing is set above the "pay." A few operators have adopted the procedure of landing and cementing the casing through the oil zone and gun-perforating it with 200–300 shots. In the gas-cap area the usual practice is to select the gas-oil contact by coring or by microscopic examination of the cuttings and to cement

[30] A. S. Donnelly, *op. cit.*

the casing a few feet below this horizon. The common size of the oil string in the early development of the field was 7-inch (outside diameter.) This permitted the use of larger cable-tool drilling bits where standard tools were to be used in drilling in; more recently the more economical 4-inch and $5\frac{1}{2}$-inch casings have been used.

In the "Wasson Deep" pool two alternatives of setting the oil-string are now permitted: (1) a continuous string of casing may be set not higher than 100 feet above the top of the 6,200-foot "pay," (2) casing may be set not higher than the top of the 5,100-foot or regular Wasson "pay" and a liner set to within at least 100 feet above the lower "pay." The top of the liner must extend 300 feet above the casing shoe of the upper oil string and must be at least 200 feet above the top of the upper "pay." In both cases the annular space between the wall and the casing must be filled with cement, as shown by temperature or other cement survey, to a point 200 feet above the regular "pay" to protect it from the waters encountered in the lower part of the San Andres formation.

DRILLING-IN PROCEDURES

After the cement plug has been drilled and the casing tested for the effectiveness of the water shutoff, the clear water used to test the casing is replaced by crude oil which is the circulating medium used while drilling in. Accurate drilling time taken at 1-foot or 5-foot intervals, and well-cutting samples taken at 1-, 5-, or 10-foot intervals give fairly good information about the geologic section. One operator, preferring to drill the pay section before setting the oil string employs mud analysis and coring for reservoir data. Ordinarily the well cuttings are inferior where this procedure is followed. The best rotary samples thus far obtained have been by reverse-circulation methods. Not only are the cuttings larger and cleaner but are more representative of the section drilled because of a smaller time lag in reaching the surface. The depth to which each well shall be drilled is either determined beforehand by adjacent well data or determined for each well individually, according to barren porosity or secondary anhydrite shown by microscopic analysis of the samples or cores as drilling proceeds. The method of determining the well depth which gives the most positive results and complete penetration of the pay section is cable-tool drilling, with microscopic examinations of the cuttings and checking of reservoir fluids by bailing and swabbing tests.

COMPLETION PRACTICES

Multi-stage-pressure acid treatments have been used in nearly all of the well completions. Three- and occasionally two-stage treatments are used preceded by a smaller wash treatment to clean the wall face. The average total treatment approximates 8,700 gallons according to V. E. Cottingham.[31] A typical three-stage acid treatment would consist of a preliminary wash or "dump job" of 700 gallons and then pressure treatments of 1,000, 2,000, and 5,000 gal-

[31] V. E. Cottingham, *op. cit.*

lons of acid to which various chemical reagents had been added to serve as inhibitors, demulsifiers, activators, and other physical and chemical modifiers. The largest treatments used in the field thus far have totalled 22,000 gallons. The large volumes of acid used have required a greater amount of swabbing to recover the additional residue water, and to clean the oil to the 2 per cent "cut" required by the pipe-line companies.

In 164 wells nitroglycerine has been used to shoot the well bores opposite the productive zones while in a few wells both acid treatments and nitroglycerine were used. The total amounts of glycerine used in individual wells have ranged from 200 to 2,100 quarts.

The average time spent in completing a well from commencement date to the time of the official Railroad Commission gauge is now approximately 5 weeks; nearly twice as much time was required in the early stages of the field. Some wells have been completed in 21 days. The acid treatments require 6–14 days.

ARTIFICIAL LIFT

Of the 1,326 producing wells in the field on March 1, 1942, 71 wells or approximately 6 per cent were produced by artificial methods; of these, 33 were pumping and 38 were by gas-lift. Most of the gas-lift wells were operated with mechanically controlled valves and several by differential pressure flow-valves. Residue gas from the Shell-Coltexo gasoline plant is returned to the wells through a network of residue lines and compressor plants at a pressure of about 200 pounds per square inch. Many of the wells placed on artificial lift have nearly enough inherent gas to flow naturally and only a small amount of agitation or residue gas is needed to cause them to flow. Nearly all artificial-lift wells are located along the north and west edges of the field.

PIPE LINES

As mentioned previously, pipe-line construction has had a marked influence on the development in the field. Four lines serve the area, wholly or partly, and are capable of moving approximately 48,000 barrels of Wasson crude per day. Considering the ability to supply, the field has insufficient pipe-line outlet. On February 1, 1942, the allowable for the field, as prorated by the Texas Railroad Commission, was 57,280 barrels of crude and the total potential of the 1,326 wells equalled 1,221,505 barrels of crude per day.

The following are pertinent pipe-line data.

Pipe-Line Company	*Size (Inches)*	*Approx. Capacity (Barrels)*	*Date Installed*	*Length (Miles)*	*Terminus*
Humble	6	20,000	Oct. 19, 1937	38	Hobbs, N.M.
Atlantic	6	12,500*	Apr. 1, 1939	33	Hobbs, N.M.
Shell	6	12,500†	Sept. 7, 1939	33	Hobbs, N.M.
Shell	6	8,000	Oct. 1, 1941	93	Big Spring, Tex.

* Restricted by amount of crude delivered to line by Richardson pipe line from the Slaughter field.
† Restricted by approximately 1,000 barrels per day of natural gasoline from the gasoline plant.

HEMPEL FRACTIONAL DISTILLATION ANALYSES OF WASSON FIELD CRUDE OIL

Fraction	*Crude Oil*	*375°F. E.P. Gaso.*	*Dr. Swt. 375°F. E.P. Gaso.*	*Gas Oil*	*Topped Crude Gaso.*	*Topped Crude after Gas Oil*	*Dist. Loss*
Yield, vol. % of crude	100.0	32.6		23.4	67.0	43.6	0.4
Analyses of Fractions							
Gravity, °API at 60°F.	32.8	57.9	57.8	36.2	22.8	16.8	
Sp. gr. at 60°F.	.8612	.7471	.7475	.8438	.9170	.9541	
Total sulphur, %	1.84	0.27		1.22	2.46	3.04	
Mercaptan sulphur, %		0.093					
R.V.P., lb./sq. in.		6.0	5.6				
Octane No., M.M.		55.5	55.0				
Octane No., M.M.+1 ml. TEL			61.0				
Octane No., M.M.3 ml. TEL			68.0				
Cold test, °F.	10			Below 0	45	65	
B.S. & W., %	0.3				0.3	0.3	
Viscosities							
Kinematic at 100°F., Cs.	4.91			2.51	33.70	472.2	
Kinematic at 210°F., Cs.					5.45	20.79	
Univ. at 100°F., Sec.	42.0			34.4	157	2181	
Univ. at 210°F., Sec.					43.7	100.8	
Aniline pt. °F.				140.7			
Aniline pt. °C.				60.4			
Cetane No.				51			
Flash, P-M., °F.					215		
Salt as sodium chloride Lbs./1000 bbl.	44						
100 Ml. Distillation							
I.B.P., °F.	135	114	113	396	420	622	
5%	195	152	158	420	447	648	
10	229	167	175	430	468	661	
20	296	192	198	448	521	684	
30	372	214	217	460	577	705	
40	462	232	233	476	624	720	
50	*561*	*248*	*249*	*493*	*648*	*732*	
60	643	264	265	507	670	744	
70	702	282	282	522	691	756	
80	734	303	303	541	699	760+	
90	757	332	329	568	718		
E.P., °F.	759	374	374	619	726	760+	
% Over	96.0	98.0	98.5	99.0	94.0	93.0	
% Bottoms		1.0	1.0	1.0			
% Loss		1.0	0.5				
% Coke by weight	3.6				5.5	7.3	
% Over at 400°F.	33.5						
% Over at 572°F.	51.0				29.0		

PRODUCTION STATISTICS

The cumulative production for the regular or 5,100-foot "pay" on Jan. 1, 1943, representing more than 6 years, has been 42,560,962 barrels of crude; in addition the "Wasson Deep" zone had produced 35,769 barrels, and the "Wasson 72" zone had produced 34,896 barrels. The annual and cumulative production of the 5,100-foot "pay" has been as follows (in barrels).

	Annual	*Cumulative*
1936	9,506	9,506
1937	314,024	323,530
1938	2,801,645	3,125,175
1939	5,934,151	9,059,326
1940	10,976,744	20,036,070
1941	13,013,979	33,050,049
1942	9,510,913	42,560,962

ACKNOWLEDGMENTS

Many of the facts and ideas given have been discussed at several times with others and through these random discussions supplemental material has been gathered—to those the writer acknowledges thanks. Specifically, the writer wishes to thank P. F. Brown, A. S. Donnelly, R. L. Blunden, and other co-workers of the Honolulu Oil Corporation for technical assistance and information, and the Honolulu Oil Corporation for permission to publish data from its files. Field data and statistics were borrowed heavily from the compilations made by V. E. Cottingham and particular thanks are extended for his generous permission to allow them to be published. To E. Russell Lloyd and Ronald K. DeFord the writer is indebted for technical assistance in preparation of the manuscript.

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VOL. 27, NO. 4 (APRIL, 1943), PP. 524-538, 6 FIGS.

GEOLOGICAL NOTES

EVIDENCE FOR UPPER JURASSIC LANDMASS IN EASTERN MEXICO[1]

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Establishment of the Jurassic age of some of the oil-producing formations of Arkansas and Louisiana has aroused interest in the possibilities of obtaining oil from sedimentary rocks of that age elsewhere in the Gulf region of the United States. However, location of Jurassic rocks within reach of the drill may be difficult, as they are overlain at all places by thousands of feet of younger rocks and probably have a strong gulfward dip. Determination of the most likely locations in Texas, Mississippi, and Alabama involves paleogeographic interpretation of all available paleontologic and stratigraphic data concerning the Jurassic of the Gulf region of the United States and adjoining parts of Mexico. The available information concerning the former region is familiar to many American geologists, but the much larger body of information concerning the Jurassic of Mexico is apparently not as well known and for the most part has, until now, been mainly of academic interest. However, the Mexican sea was widely and continuously connected with the Gulf of Mexico and must have had a similar history. An understanding of that history, particularly of northern and eastern Mexico, may be of economic importance to geologists investigating the petroleum possibilities of the buried Mesozoic rocks of the Gulf region.

The Mexican sea of Upper Jurassic time was visualized by Burckhardt[3] as a large arm enclosed on all sides by landmasses except toward the southeast in the State of Vera Cruz. The sea may have had a southern portal[4] to the Pacific Ocean but probably did not have a northern portal.[5] It was outlined in northeastern Mexico by two peninsulas extending southward from the region of Texas.[6] The

[1] Manuscript received, January 19, 1943.

[2] Geologist, United States Geological Survey.

[3] Carlos Burckhardt, "Étude synthétique sur le mésozoique méxicain," *Mém. Soc. Paléont. Suisse*, Vol. 49 (1930), p. 103.

[4] Charles Schuchert, *Historical Geology of the Antillean-Caribbean Region* (1935), p. 156. L. B. Kellum, R. W. Imlay, and W. G. Kane, "Relation of Structure, Stratigraphy and Igneous Activity to an Early Continental Margin," *Bull. Geol. Soc. America*, Vol. 47 (1936), pp. 981–83. Carlos Burckhardt, *op. cit.*, p. 104.

[5] R. W. Imlay, "Paleogeographic Studies in Northeastern Sonora," *Bull. Geol. Soc. America*, Vol. 50 (1939), pp. 1724, 1941.
———, "Possible Interoceanic Connections across Mexico during the Jurassic and Cretaceous Periods," *Proc. Sixth Pacific Sci. Cong.* (1939), pp. 423–27.

[6] Emil Böse, "Vestiges of an Ancient Continent in Northeast Mexico," *Amer. Jour. Sci.*, 5th Ser., Vol. 6 (1923), pp. 128–36. Emil Böse and O. A. Cavins, "The Cretaceous and Tertiary of Southern Texas and Northern Mexico," *Univ. Texas Bull. 2748* (1927), pp. 81–82. Carlos Burckhardt, "Étude synthétique sur le mésozoique méxicain," *Mém. Soc. Paléont. Suisse*, Vol. 49 (1930), pp. 100–04. R. W. Imlay, "Upper Jurassic Ammonites from Mexico," *Bull. Geol. Soc. America*, Vol. 50 (1939), p. 4. R. W. Imlay, "Upper Jurassic Pelecypods from Mexico," *Jour. Paleontology*, Vol. 14 (1940), p. 393.

western, or Coahuila Peninsula terminated broadly in the region of southern Coahuila and divided the Mexican sea into a large western basin and a small eastern basin. The eastern peninsula occupied what is now the eastern margin of the Sierra Madre Oriental and terminated toward the south in the states of Vera Cruz and Hidalgo. The distribution of clastic sediments suggests that south of central Tamaulipas the peninsula passed into an archipelago, and that it was bordered by islands, but as yet only the Miquihuana Island has been definitely demonstrated. As the peninsula undoubtedly influenced sedimentation in the Gulf region, the evidence from which its existence is inferred should be of particular interest to geologists concerned with the petroleum possibilities of the Jurassic formations of southern Texas.

The presence of a peninsular landmass in eastern Mexico during Upper Jurassic time is inferred from (1) an eastward lithologic change from limestones, marls, and shales in the central part of the Mexican geosyncline to a thicker section of coarse clastic sediments containing some coal and gypsum in the Sierra Madre Oriental, (2) an eastward faunal change from a dominance of cephalopods in the fine offshore sediments to a dominance of bivalves in the coarse nearshore sediments, (3) the occurrence in the Sierra Madre Oriental of early Lower Cretaceous beds that rest directly on pre-Upper Jurassic beds, and (4) the presence of Upper Jurassic beds in the coast region near Tampico, in the San Carlos Mountains of Tamaulipas, and near Camarón, Nuevo León. The character of the Upper Jurassic sediments exposed in the Sierra Madre Oriental implies a near-by source along the site of the eastern margin of the Sierra, but the presence of Upper Jurassic at short distances farther east shows that the source was either a long, narrow peninsula or a chain of islands. The Upper Jurassic localities on which these conclusions are based have been indicated on maps by Burckhardt[7] and the writer[8] and is now to be considered in more detail (Fig. 1).

The northern part of the eastern landmass is separated from the Coahuila Peninsula on the west by an embayment, as shown by (1) the occurrence of Jurassic fossils in the Sierra de Azul and Sierra de San Marcos of eastern Coahuila,[9] (2) the absence of Jurassic beds between the Permian and Trinity on the site of the Coahuila Peninsula,[10] and (3) the presence of black, carbonaceous limestone containing the Upper Jurassic ammonite *Kossmatia* and many bivalves in the San Ambrosio well No. 1, near Camarón, Nuevo León.[11] The bivalves and carbonaceous material show nearness to land but do not indicate the direction of the land.

[7] Carlos Burckhardt, *op. cit.*, p. 101.

[8] R. W. Imlay, "Upper Jurassic Pelecypods from Mexico," *Jour. Paleontology*, Vol. 14 (1940), p. 394.

[9] Carlos Burckhardt, "Étude synthétique sur le mésozoique méxicain," *Mém. Soc. Paléont. Suisse*, Vols. 49–50 (1930), pp. 83, 143–47.

[10] L. B. Kellum, R. W. Imlay, and W. G. Kane, "Relation of Structure, Stratigraphy, and Igneous Activity to an Early Continental Margin," *Bull. Geol. Soc. America*, Vol. 47 (1936), pp. 972–77.

[11] Carlos Burckhardt and F. K. Müllerried, "Neue Funde in Jura and Kreide Ost- und Süd-Mexicos," *Eclogae geol. Helvetiae*, Vol. 29, No. 2 (1936), pp. 314, 317, 320.

U N I T E D S T A T E S
GULF OF MEXICO
MEXICO
0 50 150 250
MILES
0 50 150 250
KILOMETERS
LEGEND
X — OFF-SHORE FACIES WITH CEPHALOPODS DOMINANT.
O — NEAR-SHORE OR MIXED FACIES WITH BIVALVES DOMINANT.
1. MALONE; 2. PLACER DE GUADALUPE; 3. LOS FRESNOS DEL RIO; 4. CUCHILLO PARADO; 5. SIERRA RICA; 6. SAN PEDRO DEL GALLO; 7. VILLA JUAREZ; 8. SIERRA DE JIMULCO; 9. WESTERN PART OF SIERRA DE PARRAS; 10. MIDDLE PART OF SIERRA DE PARRAS; 11. SIERRA DE RAMIREZ; 12. SIERRA DEL CHIVO; 13. PICO DE TEYRA; 14. SIERRAS DE ZULOAGA AND SOMBRERETILLO; 15. SIERRAS NEAR MAZAPIL; 16. SIERRA DE LA VENTURA; 17. SAN MARCOS; 18. MENCHACA; 19. SIERRA AZUL; 20. SAN AMBROSIO NO. 1 WELL; 21. SIERRAS BETWEEN MONTERREY AND SALTILLO; 22. CIENEGA DEL TORO; 23. NORTHEASTERN PART OF SIERRA DE SAN CARLOS; 24. LA ESCONDIDA; 25. LAS VIRGENES; 26. SIERRA WEST OF CIUDAD VICTORIA; 27. SAN LAZARO; 28. DOCTOR ARROYO; 29. MIER Y NORIEGA; 30. SIERRA DE CATORCE; 31. PEÑON BLANCO; 32. PINOS; 33. CHOCOY WELL NO. 2 & ALTAMIRA WELL NO. 11; 34. PANUCO WELL NO. 82; 35. JALPAN; 36. TAMAZUNCHALE; 37. HUAYACOCOTLA; 38. HUAUCHINANGO; 39. POZA RICA WELL NO. 8; 40. TEZIUTLAN; 41. ALMANZA; 42. CUALAC; 43. CONSUELO; 44. TLAXIACO; 45. SANTA DOMINGO IXCATLAN; 46. AMOLTEPEC; 47. CHINAMECA; 48. RIO PLAYAS.
EL PASO
SONORA
CHIHUAHUA
CHIHUAHUA
DEL RIO
COAHUILA
LAREDO
TORREON
SALTILLO
NUEVO
MONTERREY
DURANGO
LEON
TAMAULIPAS
ZACATECAS
SAN LUIS
POTOSI
TAMPICO
NAYARIT
AGUASCALIENTES
GUANAJUATO
QUERETARO
HIDALGO
JALISCO
COLIMA
MICHOACAN
MEXICO
MORELOS
PUEBLA
VERACRUZ
GUERRERO
OAXACA
TABASCO
CHIAPAS
CAMPECHE
YUCATAN
QUINTANA ROO
BAJA CALIFORNIA
SINALOA

FIG. 1.—Upper Jurassic paleogeography of Mexico.

Considerations indicating that the land lay at the west, rather than at the east, are (1) the strong evidence for a landmass extending northwestward from the region of Monterrey and (2) the probability that the major structural features of the Gulf region, such as the Rio Grande embayment, were already in existence in Upper Jurassic time.

Evidence for extending the eastern margin of the landmass as far northwest as Del Rio, Texas, is rather meager. According to Adkins,[12] the Ohio-Mexican Company's Zambrano well No. 1, about 45 miles northwest of Del Rio, began at the top of the Georgetown-Edwards limestone and, at 3,200 feet, entered arkose, which it penetrated for more than 1,300 feet. It seems probable that this arkose is of early Lower Cretaceous rather than of Jurassic age, but the writer has observed that in northern Mexico coarse deposits of early Cretaceous age are invariably underlain by coarse deposits of Upper Jurassic age, indicating that the same structural elements were involved, and that the relations of land and sea were somewhat similar at both times. Another consideration indicating the northwest extension of the landmass to the region of Del Rio is the probable genetic relationship of the Balcones fault zone of Texas to a prominent flexure that controlled the landward limits of the Jurassic and early Cretaceous sediments.[13]

Strong evidence for an Upper Jurassic landmass in eastern Mexico was found by Böse[14] in the mountains between Saltillo and Monterrey on the north and Ciénega del Toro on the south. In this region the late Upper Jurassic (Kimmeridgian to Tithonian) sediments exceed 1,000 feet in thickness. The lower and middle Kimmeridgian beds consist of carbonaceous shales and marls that in a few places are coal-bearing and locally are gypsiferous at their base. The overlying Jurassic consists mainly of red and yellow shales, sandstones, and conglomerates, of which some beds contain oysters. Coarsening of the beds toward the northeast indicates the source of the sediments and suggests that the landmass extended some distance northwest of Monterrey.

Farther south, in the mountains west and northwest of Ciudad Victoria, considerable information has been obtained by petroleum geologists[15] indicating an extensive landmass. An island existed in the vicinity of Miquihuana, as shown by the superposition of early Lower Cretaceous beds directly on early Upper Jurassic (?) redbeds,[16] but was separated from a landmass to the east by a narrow

FIG. 1.—Upper Jurassic paleogeography of Mexico.

[12] W. S. Adkins, "The Mesozoic Systems in Texas," in "The Geology of Texas, Vol. 1, Stratigraphy," *Univ. Texas Bull. 3232* (1933), p. 292.

[13] R. W. Imlay, "Lower Cretaceous and Jurassic Formations of Southern Arkansas and Their Oil and Gas Possibilities," *Arkansas Geol. Survey Inf. Cir. 12* (1940), pp. 52, 54.

[14] Emil Böse, "Vestiges of an Ancient Continent in Northeast Mexico," *Amer. Jour. Sci.*, 5th Ser., Vol. 6 (1923), pp. 130–32, 199–209. Carlos Burckhardt, *op. cit.* (1930), pp. 84, 86, 102, 103.

[15] Carlos Burckhardt, *op. cit.*, pp. 85–91. F. L. Nason, "Some Phenomena of the Folding of Rock Strata (Nuevo Leon)," *Econ. Geology*, Vol. 4 (1909), pp. 421–26. C. L. Baker [Review of], "Historical Geology of the Antillean-Caribbean Region by Charles Schuchert," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20 (1936), p. 496.

[16] R. W. Imlay, "Lower Neocomian Fossils from the Miquihuana Region, Mexico," *Jour. Paleontology*, Vol. 11, No. 7 (1937), pp. 552–59.

strait. Nearshore conditions during the late Upper Jurassic from the region of Miquihuana northward, at least as far as Las Virgenes, are shown by the presence of oyster-bearing limestones, black, red, and green shales, sandstones, conglomerates, thick masses of gypsum, and some coal. In this region, as near Saltillo, the principal masses of gypsum are at the base of the Kimmeridgian, the coal occurs a little higher in the Kimmeridgian, and the coarsest sediments are in the upper Kimmeridgian and Portlandian.

Still farther south in the Sierra Madre Oriental between Ciudad Victoria and Tamazunchale are great thicknesses of Upper Jurassic rocks[17] in contrast to much thinner Jurassic deposits of the central part of the Mexican geosyncline. Finally, the termination of the eastern landmass toward the south in the states of Vera Cruz and Hidalgo has been demonstrated by Burckhardt,[18] according to observations by himself and several other geologists on the presence at many localities of brackish-water fossils and carbonaceous deposits in the Kimmeridgian and of red-beds in the later Jurassic.

Thus, the presence of a landmass in eastern Mexico was established on stratigraphic and faunal evidence, but its peninsular character was not realized until the discovery of Upper Jurassic fossils in well sections near Tampico.[19] At first it was thought that the Jurassic beds near Tampico were formed in a small bay, but subsequent discoveries of Upper Jurassic fossils in the Sierra de San Carlos of Tamaulipas[20] and in a well section near Camarón, Nuevo León, indicated that the sea extended considerably north of Tampico. Still the peninsular nature of the landmass was questioned because of implied doubts as to the occurrence of Jurassic fossils in the Sierra de San Carlos, because the occurrence near Camarón, Nuevo León, might be west instead of east of the landmass, and because the idea was prevalent that the Gulf region of the United States and northeastern Mexico was land until some time in the Lower Cretaceous.[21] This idea was discarded with the discovery of a thick Jurassic section in Arkansas and adjoining states.

The Upper Jurassic landmass of eastern Mexico persisted into early Lower Cretaceous time and contributed sandy and conglomeratic sediments to the seas in the region between Galeana and Aramberri, Nuevo León.[22] During late Lower

[17] Arnold Heim, "Notes on the Jurassic of Tamazunchale (Sierra Madre Oriental, Mexico)," *Eclogae geol. Helvetiae*, Vol. 20, No. 1 (1926), p. 84.
———, "The Front Ranges of Sierra Madre Oriental, Mexico, from Ciudad Victoria to Tamazunchale," *ibid.*, Vol. 33, No. 2 (1940), pp. 313–52.

[18] Carlos Burckhardt, *op. cit.*, pp. 90–96.

[19] ———, *op. cit.*, pp. 994–96. J. M. Muir, *Geology of the Tampico Region, Mexico*, Amer. Assoc. Petrol. Geol. (1936), pp. 11–17.

[20] ———, *op. cit.*, p. 266. L. B. Kellum, "Geology of the Sedimentary Rocks of the San Carlos Mountains," *Univ. Michigan Studies, Sci. Ser.*, Vol. 12 (1937), pp. 39–40.

[21] Charles Schuchert, *Historical Geology of the Antillean-Caribbean Region* (1935), pp. 21, 72, 225, 290, Pl. 3.

[22] Emil Böse and O. A. Cavins, "The Cretaceous and Tertiary of Southern Texas and Northern Mexico," *Univ. Texas Bull. 2748* (1927), p. 81.

Cretaceous time it was completely submerged but marked the site of deposition of rudistid-miliolid reef limestone that contrasts with the finer-grained limestone of deeper-water origin both to the east and the west.[23] Its former position is roughly indicated at present by the abrupt eastern termination of the folds of the Sierra Madre Oriental, which apparently have been thrust against some stable mass.

Detailed studies of the Sierra Madre Oriental would be very desirable from both the economic and academic points of view. They would show the distribution of facies, the positions of the various landmasses, the relations of these lands to the Mexican sea and to the Gulf of Mexico, the times of orogeny, and the history of the region in terms of the faunal succession. Such studies, already begun by geologists of the University of Michigan in coöperation with the Geological Society of America, would, along with studies of the Cuban Jurassic, add considerably to knowledge of the Mesozoic history of the Gulf of Mexico and would thereby be of use in interpreting the history of the deeply buried Mesozoic formations of the Gulf region of the United States.

[23] J. M. Muir, *op. cit.*, p. 23, fig. 5. Carlos Burckhardt, *op. cit.*, pp. 171, 176. Emil Böse and O. A. Cavins, *op. cit.*, Pl. 19. R. W. Imlay, *op. cit.* (1937), p. 553.

NATURAL COAL GAS IN WEST VIRGINIA[1]

PAUL H. PRICE[2] AND A. J. W. HEADLEE[3]
Morgantown, West Virginia

INTRODUCTION

The term "natural coal gas" is applied to the gas which occurs naturally in coal to differentiate it from other natural and artificial gases. This gas escapes from boreholes through the coal and from mining operations and, since it commonly consists of more than 90 per cent methane, it presents an explosion hazard which demands dilution with ventilating air. More than 20 tons of air for every ton of coal produced are ventilated through some of the more gassy mines in order to prevent explosions. The volume of methane released from the mines of West Virginia is equal to, or even greater than, the state's production of natural gas. The writers believe that technology developed by the petroleum and gas industry could be adapted to the economic recovery of this gas. The first step in such a development should be investigations of how this gas is held and released by the coal seams.

[1] Manuscript received, February 4, 1943.

[2] State geologist of West Virginia.

[3] Gas analyst of West Virginia Geological Survey.

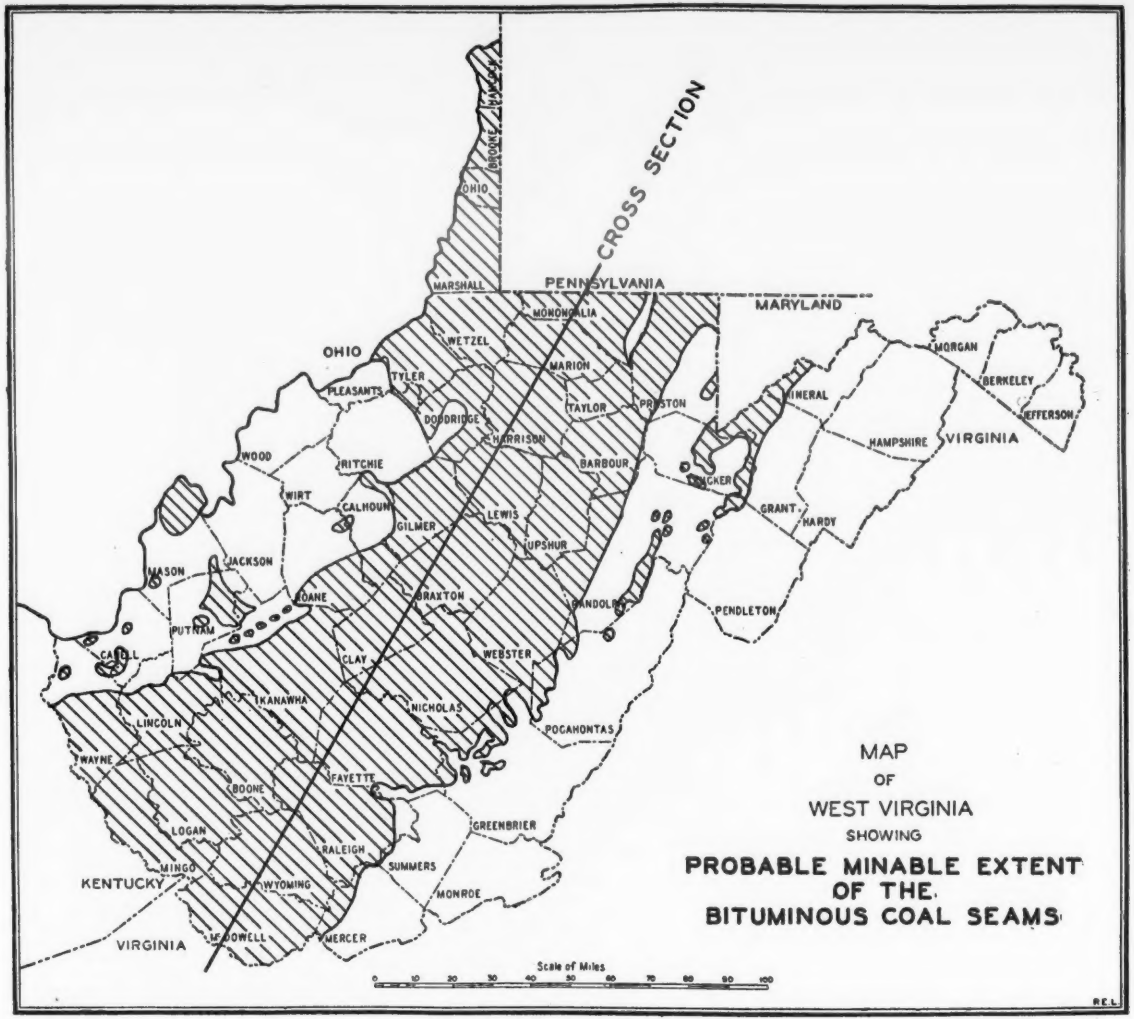
CROSS SECTION
OHIO
BROOKE
HANCOCK
MARSHALL
PENNSYLVANIA
MARYLAND
MONONGALIA
WETZEL
MARION
TYLER
PLEASANTS
TAYLOR
PRESTON
DODDRIDGE
HARRISON
MORGAN
BERKELEY
JEFFERSON
MINERAL
HAMPSHIRE
VIRGINIA
WOOD
RITCHIE
BARBOUR
TUCKER
WIRT
CALHOUM
GILMER
LEWIS
GRANT
HARDY
UPSHUR
MASON
JACKSON
ROANE
BRAXTON
RANDOLPH
PENDLETON
PUTNAM
CARROLL
CLAY
WEBSTER
KANAWHA
NICHOLAS
POCAHONTAS
LINCOLN
WAYNE
FAYETTE
BOONE
GREENBRIER
LOGAN
RALEIGH
SUMMERS
MINGO
KENTUCKY
WYOMING
MONROE
VIRGINIA
MCDOWELL
MERCER
MAP
OF
WEST VIRGINIA
SHOWING
PROBABLE MINABLE EXTENT
OF THE
BITUMINOUS COAL SEAMS
Scale of Miles
0 10 20 30 40 50 60 70 80 90 100
R.E.L.

FIG. 1

MODES OF OCCURRENCE OF GAS

GEOLOGY

The approximate area of the state underlain by one or more minable coal beds is shown in Figure 1. The same area produces large quantities of natural gas except in the row of counties along the eastern border from Preston to McDowell.

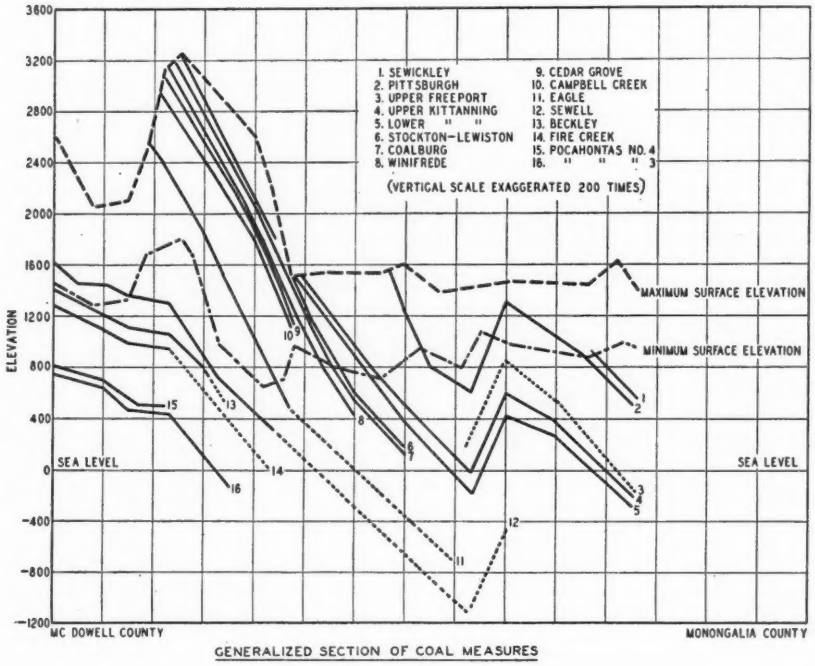

FIG. 2

The coal seams of the state have been used as reference or key horizons to map the structural geology. All of the structures in the western part of the state are reflected in the coal seams. The relation of structure to the accumulation of gas in the coal is not so well known.

Most of the commercial coal in West Virginia is Pennsylvanian in age. A maximum of approximately 5,000 feet of sediments were deposited during this period, of which 400 feet (as a maximum) is coal.

The coal seams of the state range in age from the lower part of the Permian through the Pocahontas group of the Pottsville series, as shown in Figure 2 (generalized section of Coal Measures). These coals are interbedded with numerous sandstones, conglomerates, and shales, and with the less common fresh-water

limestones. Several of the sandstones and conglomerates produce gas, oil, and salt water. In any vertical section, however, the gas, oil, and salt water production is generally below any commercial coal.

All the coals are bituminous and of low, medium, and high volatile rank. The low-volatile coals in the southern part of the state ordinarily contain the most gas per cubic foot of coal.

GAS ENTERING COAL FROM SAND RESERVOIR

The Pocahontas Fuel Company at its No. 34 mine, while mining Pocahontas No. 3 and 4 Coals under Rockhouse Branch of Horsepen Creek, McDowell County, in 1938, encountered methane gas in such quantities that mining operations were stopped in this area while several boreholes were drilled from the sur-

TABLE 1

ANALYSIS OF NATURAL COAL GAS

Well, Sample Number	County	Town	Coal Seam	Methane	Ethane	Propane	Butanes		Pentanes*	Nitrogen	Carbon Dioxide	Thv	Specific Gravity Det.
							Iso-	N-					
1	Wetzel	Coburn	Pittsburgh	83.56	8.40	3.68	.41	1.04	.36	2.10	.45	1151	.681
2	Wetzel	Coburn	Pittsburgh	92.96	1.62	.12	.01	.05	.04	3.10	2.10	968	.603
3-A	Wetzel	Allen Chapel	Pittsburgh	96.841	1.140	.287	.014	.031	.017	1.62	.04	999	.5736
4	Wetzel	Hundred	Pittsburgh	92.215	.749	.097	.020	.016	.003	1.90	5.00	955	.620
5	Wetzel	Hundred	Pittsburgh	92.868	.516	.170	.010	.031	.005	6.30	.10	946	.595
6	Wetzel	Hundred	Pittsburgh	92.76	2.02	.85	.12	.34	.18	3.73	.0	1010	.6023
19	Mason	Hartford	Freeport	92.4	.00					7.6	.0	923	.5870
565	Monongalia	Westover	Brush Creek	98.45	.00					1.50	.05	982	.5617
7	McDowell	Bishop	Poca. No. 4	93.0	.00					6.60	.40	928	.5868
8	McDowell	Bishop	Pocahontas	89.95	.00					9.30	.75	898	.6017

* These analyses are low-temperature fractional-distillation analyses by the West Virginia Geological Survey gas laboratory.

face ahead of the workings in an attempt to drain the gas off. Gas was first encountered in the sandstone about 80 feet below the surface, the release of which materially lessened the flow of gas into the mine. A total of ½ million cubic feet of gas per day was obtained from four boreholes along a 1,000-foot line. Analyses of the gas from two of these boreholes are given in an accompanying table. Even though these boreholes markedly decreased the gas escaping into the mine, large quantities of gas continued to enter through the floor, indicating the presence of another gas reservoir below the seam. Here a large quantity of water was also entering the mine along with the gas. When these wells were again visited in 1941 they were still producing some gas, and a large quantity of gas was still coming through the floor of the mine. Another well had been drilled about a mile above the first group of wells and it was producing several hundred thousand cubic feet of gas per day. These cases are given as examples of gas escaping into the coal seam from reservoirs above and below the coal where the usual methods of gas production can recover commercial quantities of gas. Contours of the area and a cross section of the wells are shown in Figures 3 and 4. A large fault (Abbs Valley), with a displacement of a few thousand feet, is immediately south of this area.

GAS FROM BOREHOLES IN COAL FACE

Lawall and Morris[4] and later Burke and Parry[5] describe conditions, where the gas is escaping into the mine directly from the coal seam. They measured the rate of flow and pressures in horizontal boreholes from a few feet to more than 100 feet into the coal. It appears from these data that the usual vertical holes into this coal would not economically remove the gas unless a wide fracture pattern could be developed around the hole.

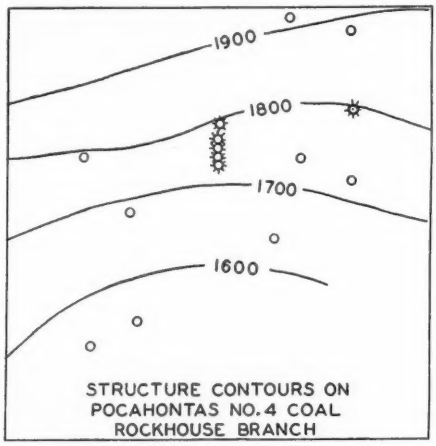

FIG. 3

It has been shown that coal expands when it sorbs gases.[6,7] Should the converse be true and the coal shrink as the gas is removed, a fracture pattern may develop sufficient to act as a drainage belt surrounding the hole.

GAS FROM WELLS

Several wells near Hundred, Wetzel County, are producing considerable volumes of gas (as much as 380 MCF. per day) from Pittsburgh coal at an approximate depth of 750 feet. Samples 1–6 (Table I) were collected in this area from the Pittsburgh coal. Well No. 3 was completed a few weeks prior to the taking of the

[4] C. E. Lawall and Lee M. Morris, "Occurrence and Flow of Gas in the Pocahontas No. 4 Coal Bed in Southern West Virginia," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 108 (1934), pp. 11–30.

[5] S. P. Burke and V. F. Parry, "Flow of Gas through Coal," *Amer. Inst. Min. Met. Eng. T. P. 607;* also *ibid.*, Vol. 119 (1936), pp. 418–32.

[6] H. Briggs, "Absorption and Discharge of Gas by Coal," *Iron and Coal Trades Rev.*, Vol. 125 (1932), p. 894.

[7] F. M. Lea, "Some Physico-Chemical Properties of Coal," *Fuel in Science and Practice*, Vol. 7 (1928), p. 430.

samples. The original pressure on the coal gas was 100 pounds per square inch. The gas from the coal in this area contains the same constituents as those of the gases from the other producing formations in the area, but the ratio of the heavier hydrocarbons to the lighter fractions is greater than that indicated by the usual analyses. The ratio of the various hydrocarbons to one another is more similar to the shale gas than any other.

The fact that these coal gases (Samples 1–6) contain considerable quantities of ethane and higher fractions indicates that the supposition that mine gases con-

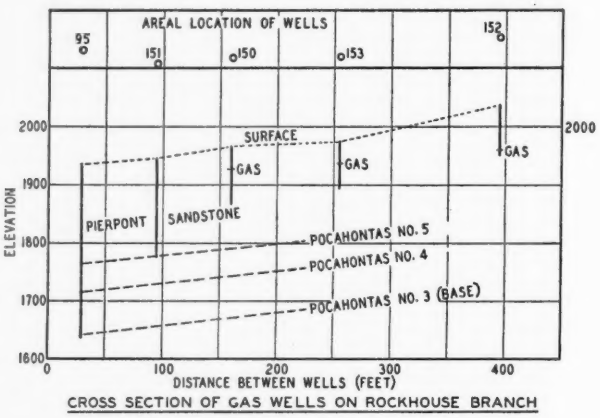

FIG. 4

tain methane as the only saturated hydrocarbon may not always be correct, and that mine gases sometimes are produced in the same manner and from the same type of source material as natural gas, the coal merely playing the rôle of a reservoir trap, just as the various sands do. However, faulty plugging and defective casing offer ready access for the natural gas in other formations to permeate the coal.

The well producing gas from the Freeport coal at the depth of 654 feet is also making salt water. Certainly the salt water is foreign to the coal horizon regardless of the source of the gas.

Well No. 565 is producing from the Brush Creek coal at the depth of 262 feet. Other wells in this area produce gas from shallow sands also. This gas may be explained by bacterial action in waters entering the formations at the outcrop.

COMPOSITION AND QUANTITY OF NATURAL COAL GAS

Very few data are available about the composition of the gas from undisturbed coal, that is, back of the fracture and drainage belt. The meager informa-

tion that is available indicates that the gas ordinarily consists of 90–98 per cent methane, 2–10 per cent nitrogen, and zero to several per cent carbon dioxide. The expected heating value would be 900–950 Btu. per cubic foot.

The quantity of methane escaping into the mine atmosphere is not known although data are available for making rough approximations. In 1936 there were 149 commercial coal mines in West Virginia that had sufficient gas in the atmosphere to warrant special safety precautions. Some of the more gassy mines are known to produce as much as 10 million cubic feet of methane each day and many of them 6 or more million so that it is readily seen that many billions of cubic feet of methane escape into the mine air each year. These 149 mines accounted for half the total coal produced in the state in 1936 although they represented only $\frac{1}{4}$ of the total number of mines. This indicates that the methane gas is being liberated more rapidly from the deeper and more extensive operations.

THEORIES OF ORIGIN

Methane is one of the products resulting from the conversion of organic matter into coals. The methane is formed by biochemical reactions and (or) by natural slow "carbonization" of the coal-forming substance.

Biochemical reactions now operative on materials other than coal are producing some of the methane in the mine atmosphere. Water samples collected from the Pocahontas Fuel Company's No. 34 mine have been producing methane in quantity for more than 4 years. Two of four samples collected in August, 1941, have produced their own volume of methane in less than 6 months; the third sample one-half its volume; while the fourth has not produced methane. These tests indicate that considerable quantities of methane are being produced in these mine waters now. Some or all of the methane found in the sand above and in the coal of the Pocahontas No. 34 mine may have been made by methane bacteria in percolating ground waters. The methane is always associated with large quantities of water in these mines.

COMMERCIAL RECOVERY BASED ON MODES OF RELEASE OF GAS FROM COAL

For the most part, methane is sorbed in the coal; the question as to whether it is adsorbed[8] or absorbed has not been answered satisfactorily. The quantity sorbed on various coals may be represented by the Freundich equation over certain pressure ranges. A chart[9] of the pressure in atmospheres, plotted against the quantity sorbed in cubic centimeters per gram of coal is shown in Figure 5. The curves for the coals are parallel where the experiments were continued below one atmosphere pressure.

[8] R. F. Selden, "The Occurrence of Gases in Coal," *U. S. Bur. Mines R. I. 3233*, p. 19.

[9] Data taken from literature cited in this paper.

It is to be noted that at 10 atmospheres many coals sorb 10 volumes of methane per gram of coal, so that there is as much gas present as could exist there, if the coal were absent. The heat of sorption[10] has been determined for Pocahontas No. 4 coal as 6,900 calories per mol for the first methane sorbed on the surface and the heat of sorption reaches a constant value of 5,200 calories after 1.55 ml. per gram is adsorbed on the coal. Actual pore space in coal has not been observed so

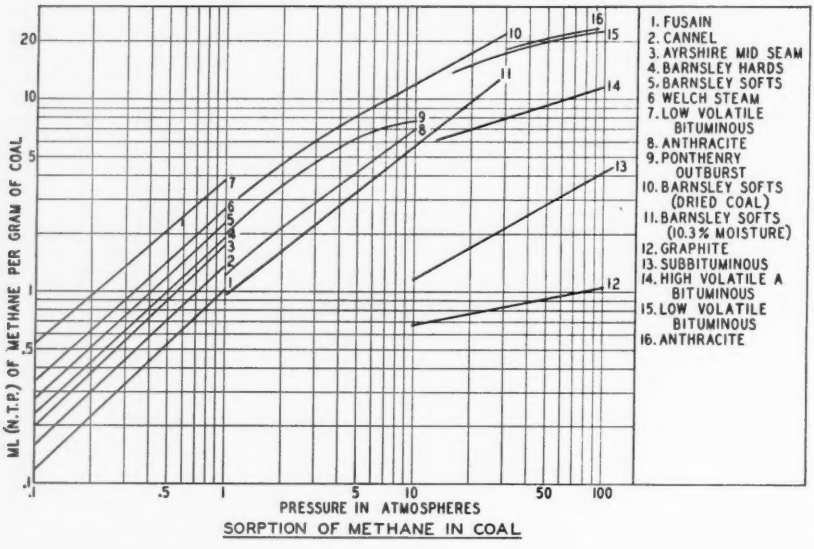

FIG. 5

that it appears that most of the methane is held in the coal by some sorption process.

Recovery techniques must consider the fact that the methane is sorbed in the coal and that the ultimate release of gas from the coal will be a desorption process. Closer drilling will be necessary than is customary in natural gas fields. It may be possible to hasten the release of the gas by shooting to create a large fracture area about the well. A method of horizontal drilling[11] has been suggested which may make it possible economically to remove this natural coal gas. It is proposed to drill horizontal holes 4,000 feet long, 800 feet apart, each hole to be cased and grouted for the first 400 feet. Each well would be connected to the surface by a vertical pipe and the entire system placed on a vacuum to hasten the flow of gas.

[10] J. B. Sutton and E. C. H. Davies, "The Adsorption of Methane by Coal," J.A.C.S. *57* (1935), 1785. Also, *Proc. West Virginia Acad. Sci.*, Vol. 10 (1936), pp. 103–05.

[11] George Ranney, "The Recovery of Natural Gas from Coal," *Eng. Exp. Sta. News*, Ohio State Univ. (June 7, 1941). Also, private communication from Mr. Ranney.

The rate of escape of the methane into the hole is of prime importance and this rate will determine the economic feasibility of any method of production. Unfortunately there are practically no data available on the rate of release of gas from virgin coal into boreholes. Several studies have been made most of which give data for the fracture and drainage belt only. Some European investigators[12] have studied the release of gas from virgin coal and have attempted to bleed off the gas with boreholes into the coal, but without success. The great variation in gas emission from different sections of the same mine and adjacent mines offers qualitative support to the idea that a wide range of permeabilities exists in virgin coal.

In some areas large quantities of gas are known to be present above and below the coal, which have ready access to the coal seam through a well developed fracture pattern. This gas can be readily recovered by drilling into the fracture system and in such cases horizontal drilling will intercept many fractures as compared with vertical boreholes.

CONCLUSIONS

Natural coal gas occurs in the coals of West Virginia in sufficient quantity to meet a large part of the state's fuel-gas requirements for many years if it can be successfully recovered.

Since methane is sorbed in the relatively non-porous coal, its release will be a desorption process. This will require close spacing of the wells and the development of a fracture zone around the well. Because of the sorptive capacity of the coal the per acre reserve is high.

In some areas large quantities of gas in rocks above and below the coal seam have ready access to the coal through a generally present fracture pattern. In such cases the effective method of removal of this gas would be to penetrate, by drilling, this fracture system.

Large quantities of methane are now being formed in many coal mines by bacteria.

[12] J. I. Graham, 'The Permeability of Coal to Gas," *Trans. Inst. Min. Eng.*, Vol. 52 (1916–1917), pp. 338–54.
———, "Composition of Gaseous Mixtures Given Off from Coal," *ibid.*, Vol. 73 (1926–1927), pp. 532–33.
F. C. Cornet, "Outbursts in France and Belgium," *Coal Age*, Vol. 35 (1930), pp. 471–74.

EMBAR FIELD, ANDREWS COUNTY, TEXAS[1]

TAYLOR COLE[2]
Midland, Texas

The Embar field is in the southwestern part of Andrews County, about 7 miles north of the Goldsmith field and about 4 miles west of the Emma field. It is on the northern part of the Central Basin platform.

The discovery well, Phillips Petroleum Company's University No. 2, Sec. 30, Block 10, University Lands Survey, was completed on May 1, 1942. The well was drilled to the depth of 7,855 feet and flowed 1,422 barrels of 44.5° gravity oil naturally in 15 hours through open 2-inch tubing and ½-inch choke with a gas-oil ratio of 672. The "pay," which was topped at 7,770 feet, is in Ellenburger (Lower Ordovician) dolomite. The porosity is, in large part, due to fracturing, and it is not possible to say at present how much of the penetrated section is effective "pay."

On February 1, 1943, there were 7 producers and 5 dry holes in the Ellenburger. One of these dry holes made a producer in the "Tubb pay" (Leonard), resulting in the discovery of the Embar Permian field. The field now contains approximately 640 proved acres and is fairly well defined by dry holes in most directions although it is believed the field will be considerably larger than 640 acres. The structure on the Ellenburger is an irregular dome with approximately 500 feet of closure and underlies a local closure on a large Permian structure. It owes its discovery to subsurface work, core drill, drilling exploration, and geophysical work.

The following stratigraphic section was drilled in the discovery well.

	Depth in Feet
Surface, Triassic and Dewey Lake undifferentiated	0–1,320
Rustler and Salado (Ochoa)	–2,480
Guadalupe series	–3,985
Leonard and Wolfcamp undifferentiated	–7,645
Wolfcamp and possible Simpson	–7,746
Ellenburger (Lower Ordovician)	Total depth–7,855

The area is important because it was the first field to produce from the Ordovician north of Crane County 50 miles to the south. The possibility of similar production underlying many northern Permian basin fields is believed to be excellent.

[1] Manuscript received, February 26, 1943.

[2] Research geologist, University Lands. Now with Lario Oil and Gas Company.

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VOL. 26, NO. 4 (APRIL, 1943), PP. 538-550, 7 FIGS.

DISCUSSION

STRATIGRAPHIC TYPE OIL FIELDS AND PROPOSED NEW CLASSIFICATION OF RESERVOIR TRAPS[1]

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Houston, Texas

INTRODUCTION

During the recent years in which "stratigraphic traps" have been so widely discussed, strict limitations on the application of the term seem to have been generally avoided. This has probably been partly intentional, in order to focus attention on an important consideration which previously had been somewhat neglected and which could be expected to become increasingly important with the gradual decrease in the number of prominent closed uplifts left to be found. But in emphasizing the importance of the stratigraphic and lithologic factors, the tendency has been to neglect the structural factors generally involved. The stage has now been reached in which application of the term "stratigraphic trap" should be more strictly limited and in which new terms should be evolved for facile reference to the various types of combination traps.

If an ethnological analogy may be permitted, referring to "White" persons *versus* American Indians, it is as if only persons with 100 per cent Caucasian blood were called "White," and those with the slightest admixture of American Indian blood were all called "Indians."

Blend terms are generally lacking in our present trap terminology. Even some structural reservoirs with a faint tinge of stratigraphic or permeability modification have been termed "stratigraphic traps."

IMPORTANCE OF STRUCTURE

That local structural deformation was an important factor in many of the areas cited in *Stratigraphic Type Oil Fields*,[3] is brought out by the authors themselves in their field descriptions and maps. Many non-technical executives, however, would simply see the impressive list of fields described under the "stratigraphic type" heading and might conclude that local structure was lacking or unimportant in most of those areas.

Quotations from the authors of some of the various contributions to *Stratigraphic Type Oil Fields* are given in the following paragraphs (with a few notes by the present writer) to indicate the importance of local structure in many of the localities described. Italics within the quotations from other authors are by the present writer.

Edison field, California.—Oil accumulation in the Upper Duff zone (Kern River series) is believed to result *from a fault seal on the northeast side* and a decrease in porosity of the zone toward the southeast.

Oil accumulation in the Lower Duff zone occurs along the *structural nose* in the porous overlapping sands, where it is sealed by impervious overlying shales.—Everett C. Edwards, p. 5.

Kern Front field, California.—The recognized zonal thinning, which is of more than local character, together with observed decrease in porosity and permeability toward the north, *combined with fault seal on the east*, in the opinion of the writer, accounts for the occurrence of oil in the field.—Everett C. Edwards, p. 15.

[1] Manuscript received, December 26, 1942.

[2] Regional geologist, Shell Oil Company, Inc., to which company the writer is grateful for permission to publish these notes.

[3] Symposium published by Amer. Assoc. Petrol. Geol. (1941).

Greasewood field, Colorado.—The Greasewood pool is not a true "stratigraphic trap" accumulation because the "wedge-edge" of the reservoir sandstone is down dip from the accumulation and the sandstone continues, with some thickness variations, up dip far beyond the locality of the pool. Accumulation of oil has been controlled in three directions by sandstone thickness, and porosity, but toward the east *the up-dip movement of the oil was stopped by the Niles fault which acts as a barrier.* . . . It is, therefore, demonstrated that the oil accumulation in the Greasewood pool is due to a combination of stratigraphic as well as structural factors.—C. S. Lavington, pp. 41–42.

Note.—From the author's maps it is difficult to see why this field should be included as a "stratigraphic type oil field." The accumulation is all within a structurally closed area, according to the maps presented, with only a small part of the closure barren, apparently due to local lack of permeability in the producing zone. This local lack of permeability appears not to have played any essential role in *trapping* the oil, but simply to have slightly restricted its areal *distribution* within the area of closure (C.W.S.).

Nikkel pool, Kansas.—The Hunton outlier pinches out at the northern limits of the pool. Hence, a trap for oil accumulation is formed by a *faulted anticline* closed on the north by a pinch-out.—A. S. Bunte and L. R. Fortier, p. 113.

Shoestring gas fields of Michigan.—The Michigan Stray gas fields of Michigan furnish a whole series of examples of shoestring sands formed as offshore sand bars on shoals in a shallow sea. The location of the shoals, and therefore of the sand bars, having been determined partly by previous erosion, *but mainly by previous anticlinal folding.*—Ball, Weaver, Crider, and Ball, p. 266.

Border-Red Coulee field, Montana and Alberta.— . . . it is inferred that the highest point on the buried ridge directly underlies the producing area. It is believed that owing to compaction of sediments which were being deposited over it this feature maintained an expression of slight relief . . . .—C. E. Erdmann and J. R. Schwabrow, p. 305.

East Tuskegee pool, Oklahoma.—Production is confined to the two apexes of the structure . . . . Though production is limited to these "highs," the structural position is of secondary importance in the Misener sand wells. The controlling factors are the presence or absence and the porosity of the Misener sand.—J. L. Borden and R. A. Brant, p. 451.

Note.—It seems to the present writer that the controlling factors are the structure *plus* the presence or absence of the sand,—factors of equal importance, considering that the oil in the Misener sand is found in definite association with the "highs." (C.W.S.)

Red Fork Shoestring, Oklahoma.—Subsurface structure is involved in concentration of the oil in the Red Fork lentil in certain areas.—Randall Wright, p. 485.

Cross Cut—Blake district, Texas.—Another feature indicated by the cross sections and by the thickness-contour map of the Cross Cut sand is the relation of the thickness of the sand to the structural features. The sand almost everywhere overlies the structurally high areas.—Edgar D. Klinger, p. 561.

Davis Lens, Hardin field, Texas.—A second unique feature of the lens is that it is a stratigraphic trap *within a structural trap.*—S. Russel Casey and Ralph B. Cantrell, p. 594.

East Texas field.—This great accumulation is, of course, intimately related to the structure and structural history of the Sabine uplift. Truncation and overlap, together with structural nosing on a large scale localized the accumulation on the flank of the uplift. (C.W.S.)

Hull-Silk field, Texas.—Accumulation in the two main sands is partly structural (anticlinal nosing and even some structural closure) and partly stratigraphic, due to wedging out of sands across the structural nose. (C.W.S.)

Noodle Creek pool, Texas.—It is believed that the accumulation of oil in the Noodle Creek pool was due to both stratigraphy and structure. . . . The oil was entrapped on the first terraces of the larger structural feature where apparently the porosity in the limestone was greatest. The *structure therefore was important* in entrapping the oil while the lack of porosity formed the stratigraphic trap for the location of the accumulation on the structure.—H. W. Imholz, pp. 707–08.

"Sand Belt," Texas and New Mexico.—Although the "Sand Belt" area of West Texas and southeastern New Mexico has been discussed as a stratigraphic trap, a study of the cross sections will show that regional and local structure as well as stratigraphy played an important part in the accumulation of the oil.—R. L. Denham and W. E. Dougherty, p. 759.

Walnut Bend pool, Texas.—Structure-contours drawn on top of the 4900-foot pay zone . . . show 60 feet of closure on this datum.—W. J. Hilseweck, p. 795.

DISCUSSION OF CLASSIFICATION OF TRAPS

In the final article[4] in the symposium, Tuttle, Hedberg, Rasmussen, and Levorsen state:

> Fields which are not here considered as stratigraphic in type include . . . fields in which the wedge-out of the reservoir rock is coincidental with local deformation as in some of the "bald-headed" fields of Oklahoma.

Here, the compilers have expressly and justifiably ruled out a type of structural accumulation in which local absence of the producing zone on the apex has modified the distribution of oil. Should not other modifications of structural accumulations be similarly excluded, where the local absence of producing zone or local "tightness" in that zone, played no essential role in *trapping* the oil and gas but simply prevented it from occupying a larger part of the structural closure? The writer is thinking particularly of such areas as Hitchcock,[5] Galveston County, Texas, University[6] (Baton Rouge), East Baton Rouge Parish, Louisiana, and Greasewood Flats,[7] Colorado. The Hitchcock structure, for instance, is a prominent uplift with several hundred feet of structural closure, and the whole producing area is within that closure. Halbouty postulates an eastward wedging-out of the Miocene producing sand. He states:

> This stratigraphic pinch-out serves as the final factor which completes the structural feature of the uplift; that is, dips to the south, west, and north are present, and the pinch-out of the sand toward the east causes the favorable trap for the accumulation of oil.

The compilers of the symposium could not be expected to be familiar with details of the local structural situation at Hitchcock, but instead of lacking east dip, it is noteworthy that the easterly dip is greater than either the northerly or westerly dip. The assumed wedgeout is thus not necessary to complete the trap. If wedging is present, it simply restricts the areal extent of the structural accumulation.

Similarly, the University, or Baton Rouge, field, Louisiana, is on a dome which has 250–300 feet of structural closure and the producing area is on the apex, entirely within the closure, in all sands producing to date. The domal nature of this uplift is clearly indicated by Halbouty's maps. However, if the sand pinch-outs are correctly mapped, the 4,100- and 4,300-foot sands constitute what might be termed "stratigraphic traps within a structural trap." The 6,200-foot sand reservoir exemplifies a stratigraphically modified structural accumulation. The main producing sand (6,400-foot sand) represents a normal, unmodified structural accumulation.

The critical distinction, then, is between a wedge-out or lensing which restricts the areal extent of a structural accumulation, and *one without which the accumulation* would not have been present.[8] Only the latter condition should logically place a given accumulation in the "stratigraphic trap" class. Of course, the time element may have had an important bearing in some such accumulations. It could be argued that the lensing sands in some places may have trapped the oil initially, and that the structural closure may

[4] Helen Fowler Tuttle, Hollis D. Hedberg, Clayton Rasmussen, and A. I. Levorsen, "Selected Bibliography of Articles Describing Stratigraphic Type Oil Fields," *Stratigraphic Type Oil Fields*, Amer. Assoc. Petrol. Geol. (1941), p. 858.

[5] M. T. Halbouty, "Hitchcock Field, Galveston County, Texas, Showing Stratigraphic Accumulation and Structure," *Stratigraphic Type Oil Fields*, pp. 641–60.

[6] *Idem*, "Stratigraphic Reservoirs in University Oil Field, East Baton Rouge Parish, Louisiana," *ibid.*, pp. 208–36.

[7] C. S. Lavington, "Greasewood Oil Field, Weld County, Colorado," *ibid.*, pp. 19–42.

[8] More rarely (for the sake of completeness), one which would constitute a trap in itself, with the structural deformation removed.

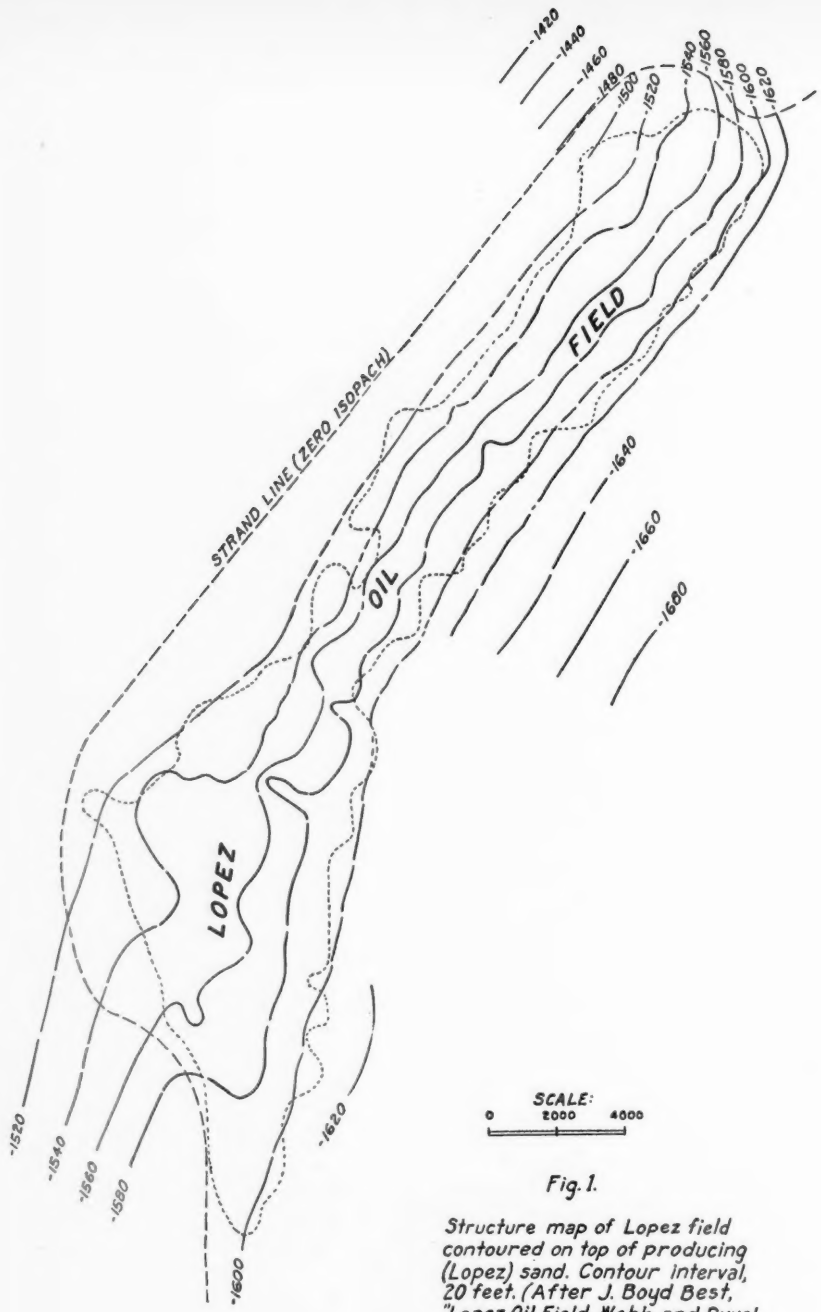

Fig. 1.

Structure map of Lopez field contoured on top of producing (Lopez) sand. Contour interval, 20 feet. (After J. Boyd Best, "Lopez Oil Field, Webb and Duval Counties, Texas." Stratigraphic Type Oil Fields (1941), Amer. Assoc. Petrol. Geol., p. 683).

FIG. 1

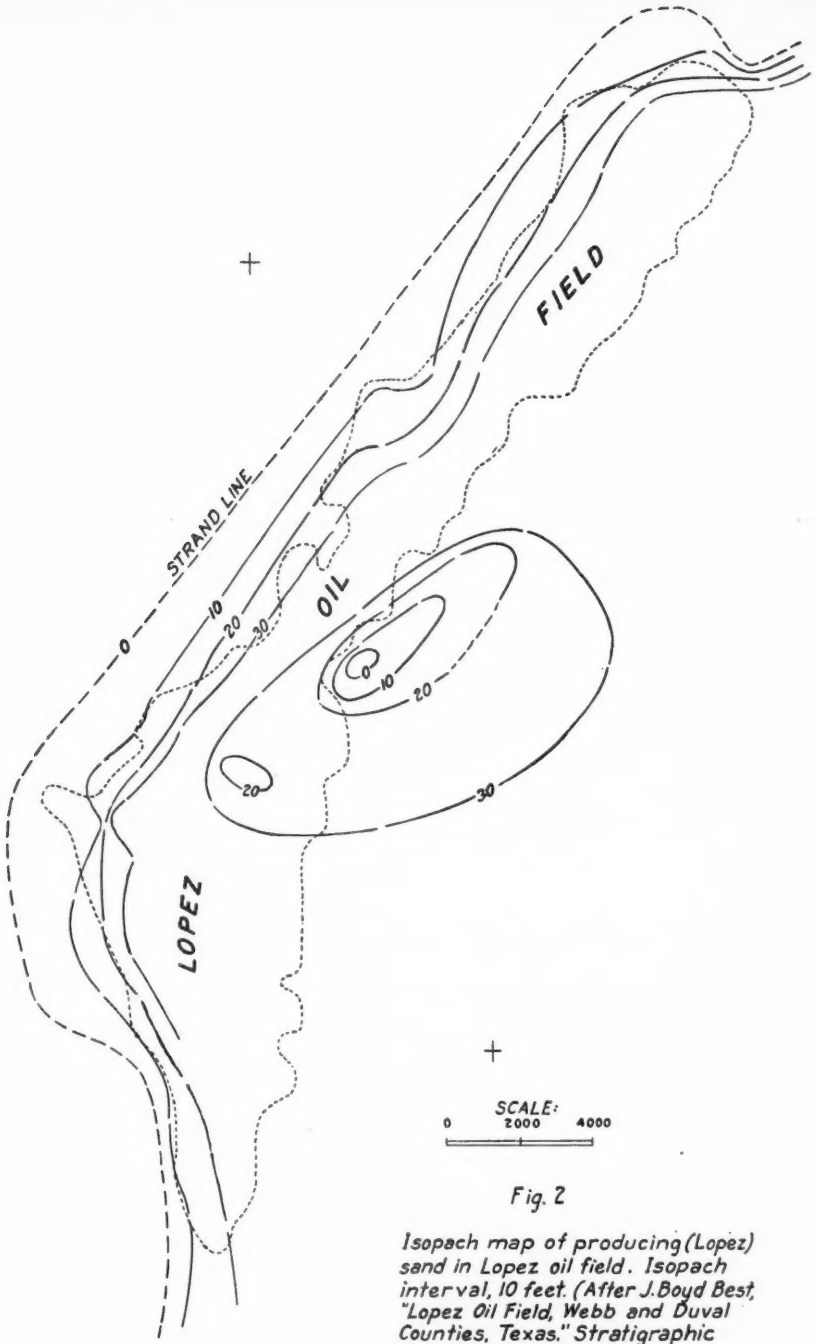

Fig. 2

Isopach map of producing (Lopez) sand in Lopez oil field. Isopach interval, 10 feet. (After J. Boyd Best, "Lopez Oil Field, Webb and Duval Counties, Texas." Stratigraphic Type Oil Fields (1941), Amer. Assoc. Petrol. Geol., p. 684).

FIG. 2

have been superinduced, perhaps even accompanied by regional tilting in another direction. Where this sequence of events might be demonstrable, it would simply constitute an example of an early stratigraphic trap converted into a later structural trap or else of a stratigraphic trap within a structural trap.

In excluding the "bald-headed" fields, the compilers showed that they did not intend that the expression "stratigraphic type oil field" should cover all occurrences of stratigraphically modified structural accumulations. The main distinction between the "bald-headed" type and the Hitchcock type is that in the former the local absence of producing zone is generally due to uplift and erosion, whereas in the latter class the local absence

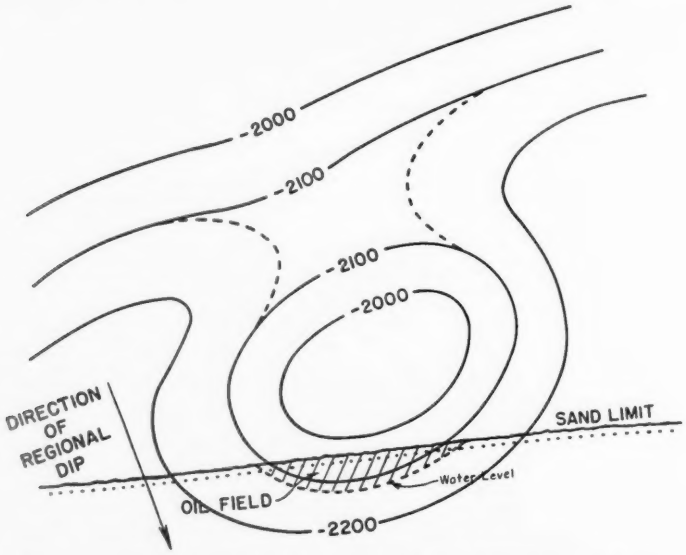

FIG. 3.—*Combination structural-stratigraphic trap.* Trap formed at edge of area of structural closure due to combination of folding and wedging.

of producing sand is commonly a depositional feature or, for lack of permeability, perhaps a diagenetic one. This may constitute sufficient distinction to warrant the exclusion of one type and the inclusion of the other, but the writer feels that in effect they are quite similar. Moreover, this sequence of uplift, truncation, and overlap has not caused such accumulations as that of the East Texas field to be excluded from the "stratigraphic type" compilation.

Most so-called "stratigraphic traps" actually represent a combination of local structural deformation and stratigraphic wedging, *neither one of which would have constituted a local trap in itself.* In the Government Wells field, for instance, the accumulation in the main producing sand is limited on the north by local folding, on the east by regional dip, on the south by a fault, and on the west by wedging-out of the sand zone. A trap would not have been present were it not for the westward or updip wedging-out of the producing sand. This may logically be classed as a "stratigraphic type" accumulation. Actually it is a *combination* structural and stratigraphic trap. The wedge-out of sand, alone, would not have constituted a trap in that locality without the laterally confining structural features.

An example of a simple stratigraphic trap is Lopez,[9] Webb and Duval counties, Texas, where an updip salient in the Lopez sand, in an area of essentially regional dip, has trapped the oil. The trap is due to the updip bulge in the wedge-edge of the sand (Figs. 1 and 2). This type is due to the pattern of *areal* development of the permeable zone. Another simple type of stratigraphic trap is one due to the pattern of *vertical* development of sand,—where the sand "builds up" to a notable convexity on its upper surface. The Dora pool,[10] Seminole County, Oklahoma, appears to be a close approach to an ideal example of this type.

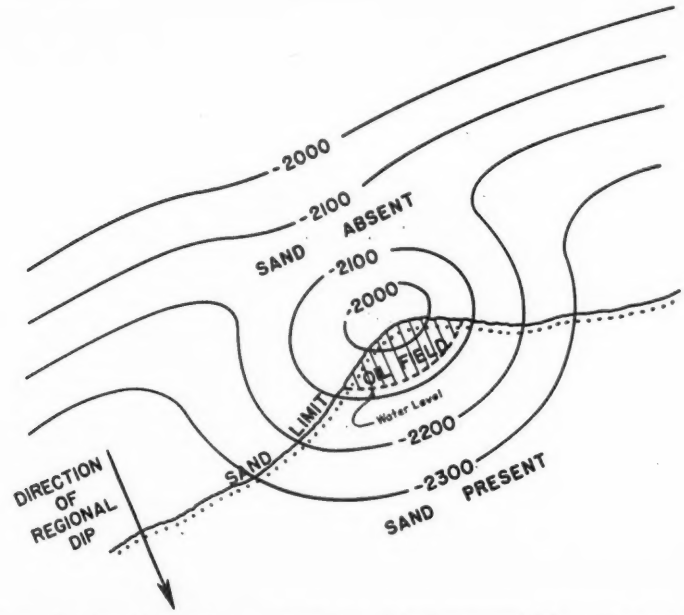

FIG. 4.—*Stratigraphic trap within structural trap.* If local structural deformation were removed, a trap would still be present due to updip salient in wedge edge of sand. Such traps are closely related to "stratigraphically modified structural traps" (as Fig. 5). They can not be differentiated from "stratigraphically modified structural traps" unless something is known of extent and distribution of sand outside local structure.

Many shoestring sands, such as the Olympic sand in the Olympic pool,[11] constitute examples of simple stratigraphic traps, although earlier anticlinal structure and consequent submarine shoaling localized some of them, and parts of others were involved in later folding.

Nearly every classification runs into a difficult border or "twilight" zone. In the case of stratigraphic *versus* structural traps, it lies chiefly in the next consideration, namely, accumulations of oil or gas occurring well up on the *flanks* of *closed* structures. There is no way of avoiding these border zones in classifications, a good example of which is the

[9] J. Boyd Best, in *Stratigraphic Type Oil Fields*, pp. 680–97.

[10] W. I. Ingham, *ibid.*, pp. 408–35. (See particularly his Fig. 4.)

[11] W. Reese Dillard, *ibid.*, pp. 456–72. (See particularly his Figs. 3 and 4.)

problem of drawing a line between high-gravity oil and condensate. In the case of asymmetrical accumulations on closed structures, the writer suggests application of the principles illustrated in Figures 3, 4, and 5.[12] If the structure has closure, but the updip wedge-edge lies regionally downdip from the closing contour, the accumulation is obviously due to the *combination* of wedging and local structural *nosing*. Figure 3 illustrates a borderline case in which oil and gas are trapped slightly higher on structure along a wedge-out where it crosses the edge of a large area of structural closure. In this example, the accumulation occupies a relatively small part of the area of structural closure. This is also considered to

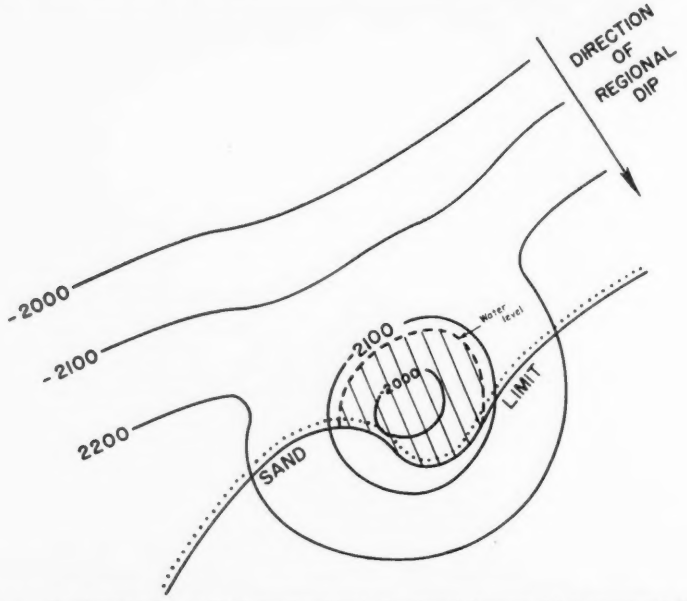

FIG. 5.—*Stratigraphically modified structural trap.* So classed because (1) if structural deformation were removed no local trap would be present, and (2) wedging was not necessary to complete trap, as in case of "combination structural-stratigraphic traps." Wedging here simply prevented accumulation from assuming completely symmetrical outline in relation to structure contours within structural closure.

represent a "combination structural-stratigraphic trap," because both the structural nosing and the wedging were necessary for the presence of a local trap in such an asymmetrical position with relation to the area of closure.

Figure 4 illustrates a "stratigraphic trap within a structural trap." A trap would have been present without the local folding. Figure 5 shows a "stratigraphically modified structural trap" in which the extent of producing sand within the closure is limited, as in Figure 4, but in which the sand is continuous updip beyond the locality shown, so that no trap independent of structure is present. If the structural closure shown in Figure 5 had not been present, the oil would have moved updip beyond the locality in question.

[12] For the sake of simplicity, the postulated accumulations are shown at the actual edges of the various sands, whereas they commonly occur near the 5-, 10-, or 15-foot net-sand isopachs, due to "splitting" of the sand and accession of silt in the extreme updip edges.

There is a further minor consideration recently brought up by Wilson,[13] who, referring to the Chapman pool, Williamson County, Texas, states:

> If we are to use stratigraphic traps interchangeably with porosity traps this then would also be a stratigraphic trap. But the reservoir rock is a serpentine and we are now confronted with a stratigraphic trap in an igneous rock.

The simplest solution, it seems, would be to restrict the term "porosity trap" to wedging-out of effective porosity in a non-sedimentary rock. The porosity and permeability in a *sediment* seems to the present writer to come justifiably within the scope of stratigraphic considerations.

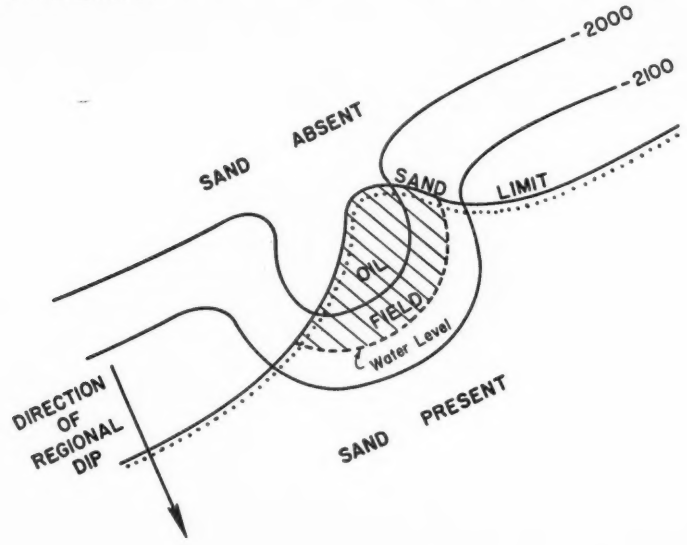

FIG. 6.—*Structurally modified stratigraphic trap.* Stratigraphic trap due to updip bulge in wedge edge which happens to lie in area of anticlinal nosing. Nosing as depicted accentuates and slightly enlarges stratigraphic trap. (Synclinal nosing in this position would correspondingly decrease normal area of stratigraphic trap.)

Heroy[14] places oil and gas reservoirs in three divisions and combinations thereof, namely, (1) depositional, (2) diagenetic, and (3) deformational. His avoidance of the word "stratigraphic" in connection with the main headings nicely circumvents this academic consideration, although he states:

> Most of those in the first two groups (depositional and diagenetic) . . . may also be classed as stratigraphic traps, while those in the third (deformational) are structural traps. While some traps are of simple types, most of them are formed by a combination of factors.

The present writer retains the term "stratigraphic" with reference to reservoir classifica-

[13] W. B. Wilson, "Classification of Oil Reservoirs," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26, No. 7 (July, 1942), pp. 1291–92.

[14] W. B. Heroy, "Petroleum Geology," *Geology 1888–1938, Fiftieth Anniversary Volume*, Geol. Soc. America (1941), pp. 535–39.

tion, simply because it has already come into such common usage that it probably is not to be dislodged from popular designations.

For greater refinement of subdivisions, Wilson's[15] classification is recommended.

PROPOSED CLASSIFICATION

The following broad classification of traps favorable for the accumulation of oil and gas is offered for every-day usage, attempting to generalize the more common types and at the same time to stress critical distinctions between various types which have been

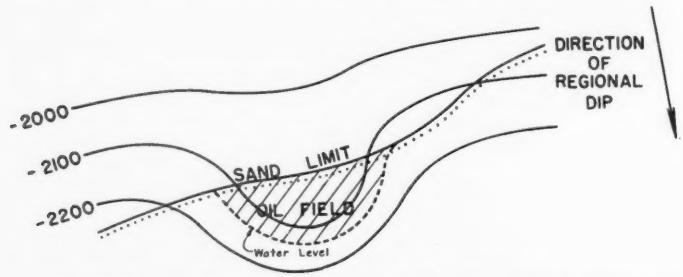

FIG. 7a.—*Combination structural-stratigraphic trap.* Anticlinal nosing and wedging-out of sand were both necessary for presence of trap in this locality. (Same principles would apply if "sand limit" in these illustrations is assumed to represent pattern of *wedging-out of permeability* in sand or limestone.)

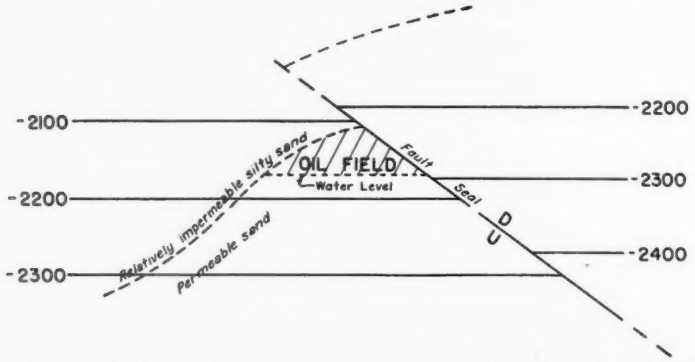

FIG. 7b.—*Combination structural-stratigraphic trap.* Combination of wedging-out of permeability plus fault seal. Neither feature alone would have constituted local trap. These represent only two of many possible combinations of structural and stratigraphic features which together may form effective traps.

popularly lumped in the catch-all "stratigraphic trap" terminology. The terms proposed are applicable to single zones only,—a given field may include several types. They may be used for either fields or prospects.

I. *Structural trap* (Wilson's I-A), wherein the trap is essentially due to structural closure (including fault closure types)

[15] W. B. Wilson, "Proposed Classification of Oil and Gas Reservoirs," *Problems of Petroleum Geology*, Amer. Assoc. Petrol. Geol. (1941), p. 442.

A. *Normal.* Areal extent of producing zone, or prospective producing zone, not notably restricted or modified by variations in stratigraphy or permeability. *Examples.*—Conroe sand zone in Conroe field, Montgomery County, Texas. Langham sand (Frio) in Amelia field, Jefferson County, Texas. Main producing sands in the Salt Creek field, Wyoming.

B. *Stratigraphically modified.*[16] Areal extent of producing zone or prospective producing zone notably restricted or modified within the area of structural closure due to local absence of the zone itself or to marked local diminution of the permeability within the zone. The pattern of the wedge-out or local "tightness" is such that a trap would not have been present without the local structural deformation.

1. Producing zone missing from apical area of the structural closure: "bald-headed" structures such as Billings field, Noble County, Oklahoma, with reference to the Simpson sand zone.
2. Producing zone or prospective producing zone (or the permeability within that zone) missing from one or more sides of the area of structural closure (Fig. 5). (Note.—Some reservoirs of this type have been described as "stratigraphic traps," for instance, the 6,200-foot sand in the University (Baton Rouge) field.)[17]

II. *Stratigraphic trap*[18]

A. *True or simple*

1. Trap wholly due to the pattern of *areal* development of a wedging permeable zone,[19] with no structural deformation involved in the trapping other than regional tilt.
Example.—Lopez sand in Lopez field, Webb and Duval counties, Texas (Figs. 1 and 2).
2. Trap wholly due to the pattern of *vertical* development or upward convexity of a permeable zone of irregular thickness, with no structural deformation involved in the trapping other than regional tilt. In such cases, the upper surface of the permeable zone shows "false" or stratigraphic reversal, with no structural reversal present at the base of the zone, or in slightly deeper markers.
Example.—Dora sand in the Dora pool,[20] which is probably part of an old sand bar.

B. *Complex.* Various combinations of stratigraphic features which together form a trap, with no structural deformation involved in the trapping, other than regional tilt. A theoretical example would be an area near the updip edge of a sand, where a trap was formed in part by actual wedging-out of the sand, and in part by "false" reversal or convexity of the upper surface.

C. *Structurally modified.* Pattern of distribution or development of a permeable zone which would constitute a stratigraphic trap in itself, but which happens to coincide with an area of structural nosing. Anticlinal nosing (Fig. 6) will accentuate and generally enlarge the normal stratigraphic trap reservoir; synclinal nosing will decrease it and may even eradicate the normal trapping effect of a slight updip bulge in a wedge edge.

D. *Within a structural trap.* Pattern of development of a permeable zone similar to types in A and B but in which the stratigraphic trap occurs within an area of structural *closure.* If the local structural deformation were removed, a trap would still be present (Fig. 4). This category is similar to I-B, insofar as the producing area alone is concerned, but differs in the relation of sand development to direction of regional dip.
Examples.—The 4100- and 4300-foot sands in the University (Baton Rouge) field, Louisiana, as portrayed by Halbouty.[21]

[16] More rarely, "porosity-limited" (referring to effective porosity), where the reservoir is not a sedimentary rock. *Example.*—Lytton Springs, Caldwell County, Texas, in weathered serpentine. The arched top of the intrusive material furnished the structural closure.

[17] M. T. Halbouty, *op. cit.*, pp. 229–35.

[18] "Porosity trap" in the relatively few cases where the reservoir is not a sedimentary rock.

[19] Includes eroded, overlapped, and sealed reservoir edges where no *local* deformation is involved. If critical local structural deformation is present, accumulations of the overlapped type are classified in II-B, II-C, or III, just as if they were depositional wedge edges.

[20] W. I. Ingham, *Stratigraphic Type Oil Fields*, pp. 408–35. (See particularly his Fig. 4.) Localization of the accumulation at Dora, however, may have been slightly influenced by folding and faulting in the southeast part of the pool.

[21] M. T. Halbouty, *op. cit.* (See his Figs. 3 and 5.)

III. *Combination structural-stratigraphic trap.* Trap due to local structural deformation (folding and, or, faulting) *in combination with* wedging-out of a permeable zone and, or, "false" reversal due to a convex upper surface of the permeable zone (Fig. 7). In other words, both the structural and the stratigraphic features are necessary for the presence of the trap, which differentiates this class from those described under II. Most presently classified "stratigraphic traps" fall in this category.

Examples.—(1) Main producing zone in the Government Wells field,[22] Duval County, Texas, in which the closure is due to a combination of folding, faulting, regional tilt, and updip wedging.

(2) Woodbine sand in the East Texas field, in which the closure is due to a combination of (1) updip truncation and overlap and (2) large-scale anticlinal nosing.[23] The structure contours close against the wedge edge of sand near the north and south extremities of the field.

[22] John Trenchard and J. Barney Whisenant, "Government Wells Oil Field, Duval County, Texas," *Gulf Coast Oil Fields*, Amer. Assoc. Petrol. Geol. (1936), pp. 631–47. (See particularly pp. 638–39.)

[23] H. E. Minor and Marcus A. Hanna, "East Texas Oil Field, Rusk, Cherokee, Smith, Gregg, and Upshur Counties, Texas," *Stratigraphic Type Oil Fields*, pp. 600–40. (See particularly their Fig. 6.)

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 27, NO. 4 (APRIL 1943), PP. 551-559,

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library, and are available, for loan, to members and associates.

GEOMORPHOLOGY: AN INTRODUCTION TO THE STUDY OF LANDFORMS, BY C. A. COTTON

REVIEW BY BURTON WALLACE COLLINS[1]
Auckland, New Zealand

Geomorphology: An Introduction to the Study of Landforms, by C. A. Cotton, Victoria University College, Wellington, New Zealand, 3d ed., revised and enlarged. xii, 505 pp., frontispiece and 491 figs. Whitcombe and Tombs Limited, Christchurch, N. Z. (1942). Price, 25s. (N. Z.); in two parts, paper covers, 10s. 6d. each.

Petroleum geologists may be interested in the subject of geomorphology for a variety of reasons—both strictly practical and more or less academic. In the first place, the study of the evolution of landforms is closely allied to that of the structure and history of the earth's crust, and forms a natural and attractive sideline for those whose main interest is in geology in the narrower sense of the word. Moreover, for the field geologist, who is almost continuously in the closest association with the natural features of the landscape, having to surmount or avoid, cross or follow, or otherwise deal with them in the course of his daily work, some knowledge of their history and meaning can not fail to add interest and variety to what at times may become a rather monotonous task.

But not only is this subject of general scientific interest to the petroleum geologist, however, for it is also in several ways of the greatest practical value. First it is widely acknowledged that oil is often found, and may in the future be found to an increasing degree, in association with unconformities; and what are a large number of unconformities but buried landscapes, or to use Professor Cotton's expressive term, fossil erosion surfaces —formed, and perhaps also buried, if by terrestrial deposits, according to the laws of geomorphology?

Secondly, for a not inconsiderable period of the earth's most recent history the only evidence at present available may be that brought to light by a study of the geomorphology of a region. Where deposits carrying within them the record of past changes are missing or infrequent, stratigraphy must give place to the study of erosional features, changes in drainage, and modifications of the forms of valleys. In this way, for example, earth movements of major importance, as well as climatic changes, may be diagnosed. And it is not impossible that earth movements of fairly recent date—recent enough to have left their mark on the surface features of a region—may be of significance in the migration and accumulation of oil. The cases of defeated and antecedent rivers may be cited in this connection, but there are many others.

Thirdly, it is already well known, and becoming more widely realized, that there is a very close relationship between the structure and the surface forms of the earth's crust. The field geologist in any district, especially in a new and unexplored area, may be greatly aided in his elucidation of the structure by a preliminary examination of the physiography. For example, it may be mentioned that not infrequently the only evidence (or at least the first discovered and appreciated evidence) for even major faults is physiographic. By giving attention early to geomorphology, moreover, the geologist may be more quickly guided to critical outcrops and sections or to localities with abundant or useful outcrops, and so save hours or even days of wasted labor.

[1] P. O. Box 10, Auckland, New Zealand. Manuscript received, January 29, 1943.

Fourthly, geomorphology touches on the province of the petroleum geologist in yet another respect—that of the origin of oil-bearing rocks. A consideration of the work of the sea along present-day coasts and of the formation of deposits on the continental shelf and slope[2] as well as of the factors affecting deltaic and estuarine sedimentation, is at least one key to a knowledge of conditions in ancient geosynclines and of the environment and necessary conditions for the deposition not only of those sediments usually considered as the source beds of petroleum, but also of those which may later become petroliferous—the reservoir rocks. In this and other ways geomorphology overlaps, and indeed forms a basis for, the important new science of sedimentology.

Professor Cotton, in the preface to the book here to be reviewed, well summarizes the case for geomorphology from the geologist's point of view in the following words.

> To geologists the form of the surface is of interest because landforms result from the operation and interaction of processes which are active also in the production, transportation, and deposition of the materials that make rocks. It has a further interest which transcends this, however, in that it gives access to a record—which is in many cases the only record available—of a late period in the history of the earth very scantily documented by stratigraphy. Farther back in geological history, indeed, there are many gaps in the stratigraphical record, erosion intervals marked by unconformities, the correct interpretation of which can be made possible only by analogy of buried landscapes with landforms and landscapes as they exist today.

Geomorphology, also in the words of the preface,

> may be regarded as a new and revised edition of *Geomorphology of New Zealand, Part I: Systematic*, which was published in 1922 (reprinted 1926) by the Dominion Museum, Wellington, as New Zealand Board of Science and Art Manual No. 3. The old *Geomorphology*, which has been out of print for some years, has enjoyed a considerable popularity notwithstanding that a rashly promised sequel which was to present a regional treatment of New Zealand landforms has failed to appear.

There is no doubt that the issue of a new and greatly enlarged edition[3] of Professor Cotton's popular textbook will be very welcome in many quarters, as the earlier book has been a well thumbed necessity in university and teachers' training colleges in New Zealand and elsewhere almost since it appeared, as well as having been received with favor by geologists and geographers throughout the English-speaking world. That its popularity was not confined to New Zealand has been a source of grievance to students in this country for many years, since the second-hand (or n+1th-hand) value of the book increased well beyond its original price, and at least one university lecturer was forced to resort to the expedient of having large sections typed and duplicated to supply his students! One critic[4] has in fact stated that the earlier editions were sold out "largely to supply the American demand."

The book is intended not only for the student and scientist, however,

> but above all for the general reader. Its concern is with a description of the natural landscape, not the structure or history of the earth's crust; but a brief account of the materials of the crust and also of processes of erosion have been included for the benefit of readers not already grounded in geology.

Dedicated "to the geomorphologists of all nations and more especially to Douglas

[2] An interesting paper on this subject by the author of the book here reviewed is "Conditions of Deposition on the Continental Shelf and Slope," *Jour. Geol.*, Vol. 26, No. 2 (February–March, 1918), pp. 135–60; 8 figs.

[3] The new edition has xii+505 pages compared with x+462 (of the same size) in the old. The number of illustrations has been increased from 443 to 492. In the new edition the figures (apart from the frontispiece) are numbered from 1 to 473, but there are 18 distinguished by the letter A—evidently added while the book was in process of compilation—quite independent of those bearing the same number and often on separate pages. The number of chapters in the old and new editions is 29 and 33, respectively.

[4] S. H. Jenkinson, "New Zealanders and Science," *New Zealand Dept. Internal Affairs Centennial Surveys 12* (Wellington, 1940). 164 pp., 8 pls. (Article on Cotton on pp. 137–45.)

Johnson of America and Henri Baulig of France," the new edition is in plan and format similar to its predecessors. Many paragraphs are identical, but the author has enlarged on several points of topical interest (for example, soil erosion, the limestone cycle, pediments, and semi-arid erosion) and omitted some sections (the chapter on "Block Mountains and Related Features in New Zealand," sections on dissected plateaus and peneplains, the structure of alluvial deposits, the law of the migration of divides, several pages on "One-cycle, Two-cycle, and Multi-cycle Mountains," *et cetera*). The reasons for some of these omissions are not clear, unless considerations of size and price were determining factors; but in the opinion of the reviewer it would have been worth while to make room for at least some of the afore-mentioned sections, even at the expense of some of the photographic illustrations, good as they are.

An unfortunate deletion is the introductory chapter, comprising sections on "The Science of Geomorphology," "The Relation of Geomorphology to Geology and Geography," "Empirical versus Explanatory Description of Land-forms," "Empirical Nomenclature," and "Literature of Geomorphology." Some of the second of these sections is included in the preface of the new edition (part quoted earlier in this review), but the reviewer regrets that in a work that will be extensively used by students very little mention is made of such important aspects of a science as its history, terminology, and literature. The value of these seven pages in the earlier editions seems out of all proportion to the space taken up.

The size-cost consideration has probably also been the reason for the omission in the new edition of all bibliographic references, except for a one-page appendix on "Reading References" in which the author commends the recent texts of Wooldridge and Morgan, Worcester, and Lobeck,[5] as well as Tyrrell's *Volcanoes* and Johnson's *Shore Processes and Shoreline Development*. "For more information regarding sources and a fuller treatment of some doctrines and theories than it has been possible to find space for in this volume," the reader is referred to the author's recent more advanced books,[6] which it is hoped will be reviewed in this *Bulletin* shortly.

Even for beginning students it seems to the reviewer that more adequate references to the admittedly vast realm of geomorphic literature should have been made. Especially could some of the more important papers on New Zealand geomorphology have been listed (including those of the author), since few of these are mentioned in the author's two other works referred to. (The previous editions contained a 5-page list of books and papers—101 items in all.)

Another fault in the reviewer's opinion is the entire absence in the text of any reference to the great names of geomorphology. Technical terms are introduced. and defined with no indication of their source or authorship. On the first page the doctrine of uniformity is discussed with no mention of Hutton, Playfair, or Lyell, and even the famous quotation "no trace of a beginning and no prospect of an end" is left fatherless. The name of W. M. Davis is indeed mentioned in the preface, where the author states that his

> treatment is intentionally Davisian in the sense that explanation is assumed to be a necessary part of landscape description. The presentation of the "normal" cycle is Davisian also; for Davis' down-

[5] S. W. Wooldridge and R. S. Morgan, *The Physical Basis of Geography. An Outline of Geomorphology*. Longmans, Green and Company, London (1937). 445 pp., 272 figs.

P. G. Worcester, *A Textbook of Geomorphology*. Van Nostrand, New York, and Chapman and Hall, London (1939). 565 pp., 375 figs.

A. K. Lobeck, *Geomorphology: An Introduction to the Study of Landscapes*. McGraw-Hill, New York and London (1939). 731 pp., many unnumbered pls., figs., and maps.

[6] C. A. Cotton, *Landscape as Developed by the Processes of Normal Erosion*. University Press, Cambridge (1941). xviii and 301 pp., frontispiece and 44 pls., 214 figs.

———, *Climatic Accidents in Landscape Development*. Whitcombe and Tombs Ltd., Christchurch, N. Z. (1942). xx and 354 pp., colored frontispiece and 58 pls., 149 figs.

wearing theory is accepted in explanation of the origin of peneplains without reference to alternative hypotheses of slope retreat.

In addition to the differences already mentioned, several sections in the new edition have been re-arranged or largely rewritten. These include the chapters on "Landforms Associated with Faults," "Aridity and the Work of Wind" (two chapters instead of one), "Glaciation," "Volcanoes and Igneous Action" (three chapters instead of two), and "Coastal Outlines" (three chapters instead of two). The author has in many cases (for example his new and extended classification of shorelines, including those of transverse deformation)[7] drawn upon his recent articles in the *Journal of Geomorphology* and other publications.

From these articles also American geologists may be familiar with Professor Cotton's block diagrams and sketches, many of which enrich the present work. For accuracy, clarity, and even beauty these leave nothing to be desired, and should be particularly helpful in enabling students to gain a three-dimensional picture of the relation between geological structure and surface forms. In addition to the line drawings are sketch-maps where necessary and numerous photographs of geomorphic features not only in New Zealand but also from all parts of the world—some random examples are: Rocky Mountains, Colorado; Magdalena Valley, Colombia; the Rhine, Germany; Death Valley, California; Southern Tableland, New South Wales; Mount Monadnock, New Hampshire; Dolomite Alps, South Tryol; Vulcan Island, Rabaul, New Britain; Western Samoa; Gros Ventre Landslide, Wyoming; and so on. Outstanding among the new photographs of the New Zealand landscape appearing in this edition, must be mentioned the aerial views (mainly high obliques) taken by V. C. Browne of Christchurch—outstanding both for their pictorial effect and for the admirable manner in which they illustrate the processes and effects of erosion.

Finally it must be emphasized that although written by a New Zealander and originally published under the title *Geomorphology of New Zealand*, this book will have an appeal far beyond the shores of its home country. To quote Jenkinson,[8] on

> the remarkably diverse outlines of the New Zealand landscape. Here ancient rock formations were uplifted from the sea in recent geological time, and have since been and are being subjected to the wearing influences of ice, weather and volcanic action to an extent unsurpassed elsewhere. The result is that the New Zealand land- and sea-scape is a veritable museum of geomorphological processes, since all the varied influences that alter the earth's crust are carrying on their work continually about us in comparatively accessible regions.

New Zealand not only possesses the largest existing glaciers outside the polar regions (the Tasman Glacier has an area of 20 square miles, while on the other side of the Southern Alps the Franz Josef and Fox glaciers descend into semi-tropical rain-forest only 700 feet above sea-level), but also includes such varied landscapes as the semi-arid plateaus of Central Otago; the "Thermal Wonderland" of the Taupo volcanic district—including Rotorua, Mecca of tourists, with its geysers, boiling pools and sinter terraces; active and extinct volcanoes, such as Ngaruhoe and Egmont, respectively; and southwestern Otago with its numerous branching fiords;—all within a mere hundred thousand square miles. But, as already indicated, for examples of landforms Professor Cotton does not limit himself to this microcosm of geomorphology, but carefully selects his illustrations from all corners of the world.

Despite the reviewer's criticisms—mainly of sins of omission—the book is eminently worthy to take its place as an introductory textbook beside those mentioned in the fifth footnote.

[7] C. A. Cotton, "Shorelines of Transverse Deformation," *Jour. Geomorphology*, Vol. 5, No. 1 (February, 1942), pp. 45–58, 8 figs.

[8] S. H. Jenkinson, *op. cit.*, p. 140.

OIL AND GAS FIELD DEVELOPMENT IN UNITED STATES 1941, BY NATIONAL OIL SCOUTS AND LANDMEN'S ASSOCIATION

REVIEW BY LEE H. CORNELL[1]
Wichita, Kansas

Oil and Gas Field Development in the United States, Year Book 1942 (Review of 1941). Edited by Edw. C. Harman. 790 pp., maps, tables, charts (7.75×10.50 inches). Published by National Oil Scouts and Landmen's Association, Austin, Texas. Price $7.50, cloth bound.

The twelfth annual year book of the National Oil Scouts and Landmen's Association contains in one volume of 790 pages a most comprehensive report of all phases of the oil industry in the United States for the year 1941. Produced for the first time by the planograph method, the volume maintains the same high standard of quality as previous volumes.

The volume includes a complete review of the drilling, leasing, and geophysical activities in 27 states. Of the non-producing states which were explored to some extent during 1941, only North Dakota and South Dakota are not mentioned in detail. These states are, however, mentioned briefly in some of the leasing and drilling tables for the nation. In addition to the aforementioned activities, the book contains a mass of statistical information in the form of charts, graphs, and tables, numerous structural and development maps, and an appendix of 45 pages which includes numerous special articles and reprints from various trade journals.

The true value of this publication can be appreciated only by careful examination of the volume.

[1] Manuscript received, January 30, 1943.

RECENT PUBLICATIONS

ARGENTINA

*"Natural Gas in Argentina and Its Reserves," by Julio V. Canessa, Carlos A. Delorme, and Teofilo M. Tabanera. *Bol. Inform. Petrol.*, Vol. 19, No. 219 (Buenos Aires, November, 1942), pp. 10–16. In Spanish.

*"Geology of the Gulf of San Jorge," by Alejandro Piatnitzky. *Ibid.*, pp. 49–63; 13 figs. In Spanish.

ARIZONA

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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MEMORIAL

WILLIAM WEAVER KEELER
(1897–1943)

William Weaver Keeler passed away very suddenly on the night of January 3, 1943, just before retiring in his hotel room at Topeka, Kansas. He had just started on a trip through the State of Kansas with Joseph E. Morero, chief geologist of Skelly Oil Company. His death, the result of a heart attack, brought an end to his untiring and willing efforts, joyfully given even to the last hour for his chosen company, first the Minnehoma Oil and Gas Company and next the Skelly Oil Company, whom he has so proudly served for the past twenty-two years. His passing away has been a severe shock to his relatives, his company, and his many friends.

He was buried in the Rose Hill Mausoleum, Tulsa, Oklahoma, January 6, 1943.

William Weaver Keeler, better known as "Bill," was born in Pueblo, Colorado, January 8, 1897. He moved to Tulsa, Oklahoma, with his parents in August, 1906. He attended Tulsa High School for 2 years, then Kendall College at Tulsa for 2 years, graduating in the spring of 1916. In the fall of 1916 he entered the Missouri School of Mines at Rolla, Missouri, from which he graduated in 1920, receiving a degree of Bachelor of Science in Mining Engineering.

While attending the Missouri School of Mines and prior to his graduation he was employed by the United States Geological Survey in the topographical division, at Washington, D. C., receiving a course of training in topographic mapping. Later he did field work in Maryland, North Carolina, South Carolina, and Georgia. In the early part of 1918, he enlisted in the United States army and was attached to a unit that made topographic maps of artillery firing ranges located in this country on a metric scale to correspond with European maps. After being discharged from the United States army at Pensacola, Florida, he stayed there another 6 months working for the United States Engineers (who took over the mapping project started by the army), returning to the Missouri School of Mines in the fall of 1919.

After graduating from the Missouri School of Mines, he began work for the Minnehoma Oil and Gas Company, Tulsa, Oklahoma, as instrument man under Emil Kluth. In 1921 and 1922 his work consisted of mapping surface geology in eastern Kansas and the Okmulgee district of Oklahoma. During the same period he did his first independent mapping of surface geology in the Flint Hills of Kansas, finding a structure that resulted in production, being the Grand Summit pool, in T. 31 S., R. 8 E., Elk County, Kansas. He spent the summer of 1922 in California as assistant to Mr. Kluth in mapping the subsurface structure of the Santa Fe Springs and Signal Hill fields, also doing surface work in various parts of the Los Angeles basin.

In January, 1923, he became chief geologist of the Minnehoma Oil and Gas Company at Tulsa. He mapped areas in detail from Okfuskee County through Hughes and Seminole counties in Oklahoma. He also detailed areas in Kansas and New Mexico.

In 1924 he began subsurface work in Kansas and Oklahoma. He also covered areas in Fort Collins and Craig districts of Colorado and northwestern Colorado. He also covered parts of the Panhandle and San Antonio districts of Texas; also parts of Sweetwater County, Wyoming.

In 1927 the geological department of the Minnehoma Oil and Gas Company was enlarged through his management and he obtained and held the respect of all those serving under him. He managed this department until the latter part of 1930 and was then sent to Fort Worth, Texas, to organize and head a geological department for the Getty Com-

panies operating in Texas and New Mexico. General business conditions affected this new undertaking and in January, 1931, he came back to Tulsa and served as chief geologist for the Minnehoma Oil and Gas Company until its operations were taken over by the Skelly Oil Company in May, 1938.

During his career as chief geologist for the Minnehoma, the company prospered and much of its production was due to his efforts and skill as a petroleum geologist.

After joining the geological staff of the Skelly Oil Company, he was made district geologist, the district including the states of Illinois and Indiana with offices at Mattoon, Illinois. Later he moved to Evansville, Indiana.

He was successful in his work for Skelly Oil Company in Illinois and Indiana and on July 1, 1942, was made division geologist for Kansas, Nebraska, Illinois, Indiana, and Michigan, moving to the home office at Tulsa, Oklahoma. He was serving in this capacity at the time of his death.

He married Hazel Dyer of Tulsa, Oklahoma, whom he had known for many years, on December 19, 1938, at St. Louis, Missouri.

While in college, Bill was elected to membership of the Kappa Sigma and Sigma Gamma Epsilon fraternities. He also became an active member of the American Institute of Mining and Metallurgical Engineers. On September 17, 1924, he became an active member of the American Association of Petroleum Geologists, being sponsored by Luther White, V. H. McNutt, and V. H. Hughes. He was an active member of the Tulsa Geological Society and served as its secretary-treasurer during the term of 1929. Bill was also a member of the Petroleum Lodge No. 474 A.F. & A.M. at Tulsa, Oklahoma.

He is survived by his wife, Hazel Keeler, his mother and stepfather Mr. and Mrs. J. E. Graber, all of Tulsa, Oklahoma; a half-brother, Paul Graber, professor of business administration at Oklahoma A. & M. College, Stillwater, Oklahoma.

About 3 months previous to his death, his brother Edgar A. Keeler, also a member of the A.A.P.G., met a similar death, leaving as his survivors, his wife Ruth Keeler and two small sons, Bill and Bob also of Tulsa, Oklahoma.

Bill had little time for sports but was a football enthusiast, attending all the games that he could find time to attend. He occasionally participated in golf and through this interest he acquired several close friends who will always miss his presence on the golf course. He was an ardent reader and as a hobby would file different articles of interest for future reference, which he gladly shared with his co-workers. He was very quiet, retiring and sincere, yet always jolly. He possessed a keen insight into geological problems and always presented his reports and maps in the most neat, artistic and complete form. He expressed his views with full confidence always leaning toward the most conservative side. He was very firm in his beliefs and convictions but was ready at all times to weigh different views. He was fair in any decision and always loyal to his company. These higher qualities won for him many true and lasting friends who have enjoyed his pleasant companionship and will always miss his winning smile. They are glad to have known such a sterling character and their memory of him will be held in the highest esteem.

B. RIXLEBEN

ADA, OKLAHOMA
March 2, 1943

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 27, NO. 4 (APRIL, 1943), PP. 567-568

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

New officers of the Ardmore Geological Society, Ardmore, Oklahoma, are: president, C. E. HANNUM, The Texas Company; vice-president, J. P. GILL, Sinclair-Prairie Oil Company; secretary-treasurer, J. M. WESTHEIMER, Samedan Oil Corporation, Box 959, Ardmore.

KENT K. KIMBALL, consulting geologist, Tulsa, Oklahoma, spoke on "The Making and Use of Topographic Maps," before the Tulsa Geological Society, February 15.

RAY L. SIX, of the Department of Geology, Oklahoma A. and M. College, Stillwater, discussed the "Geology and Oil Possibilities of China," before the Tulsa Geological Society, March 1.

CLAUDE N. VALERIUS, Barnsdall Oil Company, of Texarkana, Arkansas, talked on "The Geology of Midway Field, Lafayette County, Arkansas," at the March 1 meeting of the Shreveport Geological Society.

The officers of the New Orleans Geological Society, New Orleans, Louisiana, are: president, J. W. HOOVER, The California Company; vice-president, H. C. PETERSEN, Freeport Sulphur Company; and secretary-treasurer, W. J. GILLINGHAM, Schlumberger Well Surveying Corporation, 452 Canal Building, New Orleans. The Society meets the first Monday of every month, 7:30 P.M., St. Charles Hotel.

The Study Group of the Problem of Well Spacing sponsored by the Pacific Section of the Association has completed its sessions and is planning to prepare a paper for publication in the *Bulletin*. This group had seven meetings under the leadership of STANLEY C. HEROLD. The method of approaching the problem by a series of curves was used and the Bell zone of the Santa Fe Springs was used as a working example as the data on that zone is virtually complete. Notes and plots of the 26 curves used in the calculations were prepared on ½ scale roto-print for the use of the members of the group. Extra copies were offered at the meeting of the Pacific Section at $1.00 each and a few still remain to be sold at that price, by FRANK S. PARKER, Wilshire Oil Company, Bendix Building, Los Angeles.

The Pacific Section is now sponsoring a study group on the Economic Aspects of Oil Property Valuation under the leadership of PAUL PAINE, author of the recently published book on that subject. This group met February 6 and expects to have a series of meetings once or twice a month until the subject is covered adequately. Persons interested in this study group should communicate with GLENN H. BOWES, Continental Oil Company, Edison Building, Los Angeles.

The Houston Geological Society held its regular meeting, February 18, at the Texas State Hotel. The local sub-committee on stratigraphic nomenclature presented its proposed geologic correlation chart for the Houston district for discussion by the Society before presenting it to the supervising committee. Members of the local committee are: CARL B. RICHARDSON, chairman, LON D. CARTWRIGHT, JR., SHIRLEY MASON, F. W. ROLSHAUSEN, and C. W. SANDERS. The chart was presented and discussed by CARL B. RICHARDSON. Sixty members were present.

The newly elected officers of the San Joaquin Geological Society are: chairman, WALLACE L. MATJASIC, Honolulu Oil Corporation; vice-chairman, ARTHUR FREDERICK

PETERSON, The Ohio Oil Company; secretary-treasurer, R. L. HEWITT, Tide Water Associated Oil Company, Bakersfield, California. At the monthly meeting on January 12, THEODORE K. SAWYER, Schlumberger Well Surveying Corporation, gave a paper on "Schlumberger Dipmeter Surveys," and Lieutenant Colonel LEE B. GOFF, JR., executive officer of Minter Field and a graduate geologist, recounted some of his experiences in Mexico. On February 9, GLENN C. FERGUSON, of the Union Oil Company, spoke on "The Upper Miocene (Reef Ridge-McLure) of the San Joaquin Valley."

LOWELL REDWINE has resigned as core analyst for the Superior Oil Company at Rio Bravo to become geologist for the Honolulu Oil Corporation at San Francisco, California.

C. MAYNARD BOOS, of Denver, Colorado, is now employed by the War Production Board as assistant technical adviser in the non-metallic section of the Mining Equipment Division. His address is 6917 Carleton Terrace, College Park, Maryland.

KATHARINE CARMAN, of West Frankfort, Illinois, has left the affairs of the Buckhorn Oil Company in the hands of her partner, M. J. HANAGAN, and has gone to Washington with the Petroleum Administration for War.

WILLIAM H. CURRY, formerly geologist for the Wellington Oil Company, San Antonio, has recently joined the geological staff of the Atlantic Refining Company, Dallas, Texas, as research geologist.

DAVID H. GRAHAM is newly associated with Kinetic Chemicals, Inc., Box 36, Arrey, New Mexico.

SIDNEY A. STUBBS, geologist for McCloskey and Company of Philadelphia, Pennsylvania, has changed his address from Tallahassee to Box 132, Bradenton, Florida.

RAYMOND S. HUNT has moved his consulting office from Grand Rapids to his residence at 405 South Main Street, Mount Pleasant, Michigan.

NEWELL M. WILDER, 155 Hamilton Park, Lexington, Kentucky, is a captain in the Army, stationed at Camp McCoy, Wisconsin.

W. B. FERGUSON, Fluorographic Exploration Company, has moved from Brenham, to the Second National Bank Building, Houston, Texas.

JACKSON M. BARTON has been transferred from the Oklahoma City district to the Midland, Texas, district of the Magnolia Petroleum Company.

THOMAS I. ANDERSON is on leave from the Pure Oil Company, Bakersfield, California, serving with the Coast Artillery at Hawaii.

GEORGE H. ANDERSON, formerly with the Texas Power and Light Company, Dallas, is now with the Lone Star Steel Company at Daingerfield, Texas.

CHESTER D. WHORTON is now located at Navy 1925, New York City.

In the list of members in military service which appeared in the October, 1942, *Bulletin*, it was erroneously stated that HUGH HAMILTON BEACH was a lieutenant in the Royal Canadian Air Force. He is with the Geological Survey of Canada, Ottawa, Ontario.

JAMES R. JACKSON, JR., is a captain stationed with the Coast Artillery at Ventura, California.

Lieutenant W. A. CLARK, JR., is Soil Conservation Officer, U. S. Naval Air Technical Training Center, Norman, Oklahoma.

WILLIAM N. BOOTH, formerly consultant of Bakersfield, California, is a 1st lieutenant with the U. S. Marine Corps at Quantico, Virginia.

J. B. WHISENANT and JOHN TRENCHARD have opened a consulting office in the Trinity Building at Fort Worth, Texas.

REX TOWNSEND is newly connected with the Office of the Petroleum Adviser, Department of State, Washington, D. C.

VINTON A. BRAY has returned to Caracas, Venezuela, where his address is The Texas Company, Apartado 267, after having been in the United States since October.

B. H. GROVE has accepted the position of principal analyst for petroleum with the Board of Economic Warfare, Washington, D. C.

J. H. MCCAMMON is with the Petroleum Administration for War, Natural Gas and Natural Gasoline Division, Washington, D. C.

Lieutenant RAY E. PEARSON is at the Merced Army Flying School, Merced, California, as an instructor in navigation and meteorology.

ALBERT F. WOODWARD, formerly with the R. R. Bush Oil Company, Long Beach, California, is a 2d lieutenant stationed at Camp Claiborne, Louisiana.

FRANK G. EVANS, formerly connected with Shell Oil Company, Inc., of Houston, Texas, is attending the U. S. Naval Air Navigation School, Hollywood, Florida.

GEORGE B. STONE is in the Naval Ordnance Laboratory, U. S. Navy Yard, Washington, D. C.

REGINALD G. RYAN, 509 West Fifth, Coffeyville, Kansas, is chief field engineer at a defense plant being built in Coffeyville.

DAVID MORGAN EVANS is an ensign in the Navy, on leave of absence from the Honolulu Oil Corporation. He may be addressed at 1505 W Street, Anacostia, D.C.

EDWARD J. FOLEY, formerly in the producing department of the Standard Oil Company of New Jersey, New York City, is now with the Imperial Oil Company Canol Project, P. O. Box 129, Edmonton, Alberta.

JAMES R. DAY, Amerada Petroleum Company, is a 2d lieutenant in the Army and is located in Wilmington, California.

Z. E. STUCKY, formerly district geologist for the Cities Service Oil Company at Wichita, Kansas, has been transferred to the geological department of that company in Bartlesville, Oklahoma, where he is assistant division geologist for Kansas.

Lieutenant GEORGE S. COREY, on military leave from Shell Oil Company, Inc., is on an island somewhere in the south Pacific area and may be addressed 18th Photo Mapping Sqd., A.P.O.-708, c/o Postmaster, San Francisco, California. Corey was asssistant district geologist at Midland, Texas.

Lieutenant WILLIAM H. ALLEN, on military leave from the West Texas division of Shell Oil Company, Inc., is addressed care of Hdq. 7th Inf. Div., G-3 Section, A.P.O. #7, Ft. Ord, California.

Lieutenant ALFRED R. LOEBLICH, JR., has been transferred from Fort Sill, Oklahoma, to the Headquarters Battery, 932nd Field Artillery Battalion, Camp Gruber, Oklahoma. Mail can still be addressed to him in care of the Department of Geology, Tulane University, New Orleans, Louisiana.

ADDITIONAL MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

(Continued from p. 561)

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J. K. Murphy, William E. Horkey, Paul E. M. Purcell

Alfred William Farmilo, Edmonton, Alta., Canada
W. C. Bednar, V. E. Monnett, C. G. Lalicker

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Fred M. Bullard, W. A. Bramlette, F. L. Whitney

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Bertram Wolfram, Jr., Galveston, Tex.
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G. W. Schneider, R. A. Steinmayer, Gordon I. Atwater

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Manager of Well Log Bureau - Harvel E. White

Regular Meetings: 7:30 P.M., Geological Room, University of Wichita, first Tuesday of each month. Visitors cordially welcomed.

The Society sponsors the Kansas Well Log Bureau which is located at 412 Union National Bank Building.

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Cities Service Oil Co., Mt. Pleasant

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Meetings: First and third Wednesdays of each month from October to May, inclusive, at 7:30 P.M., Edwards Hotel, Jackson, Mississippi. Visiting geologists welcome to all meetings.

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Dinner meetings will be held at 7:00 P.M. on the first Wednesday of every month from October to May, inclusive, at the Ardmore Hotel.

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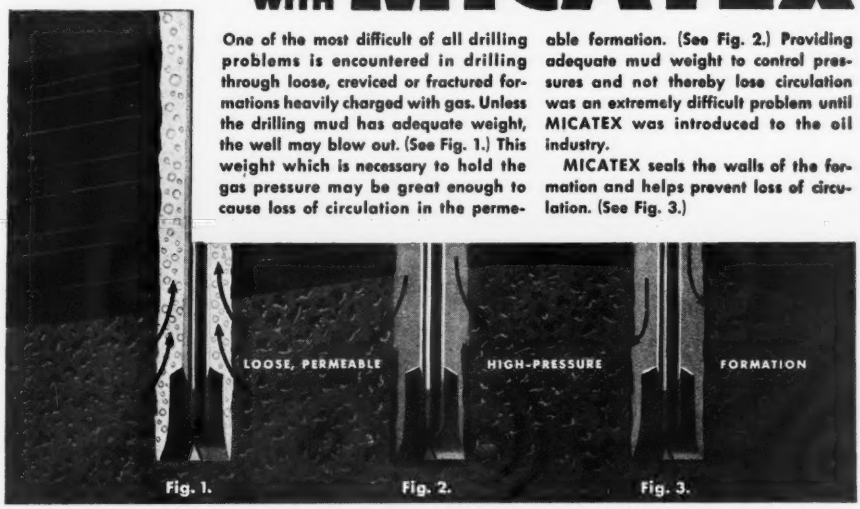

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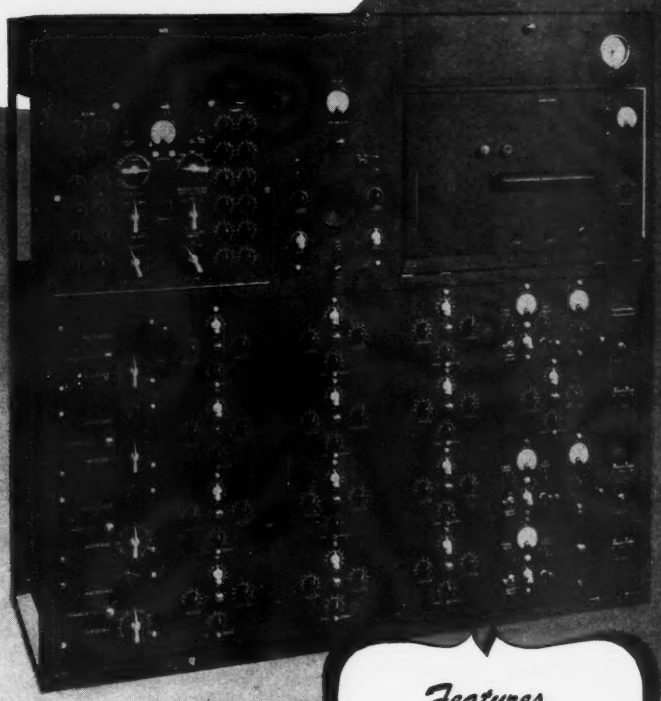

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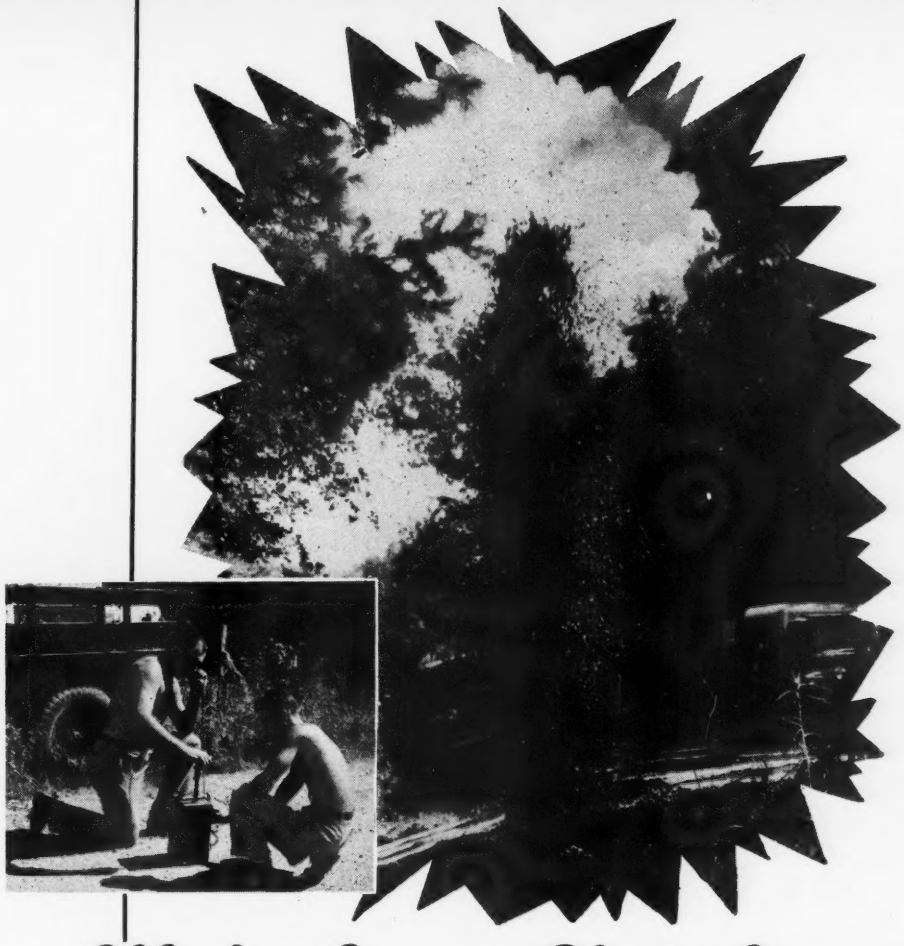

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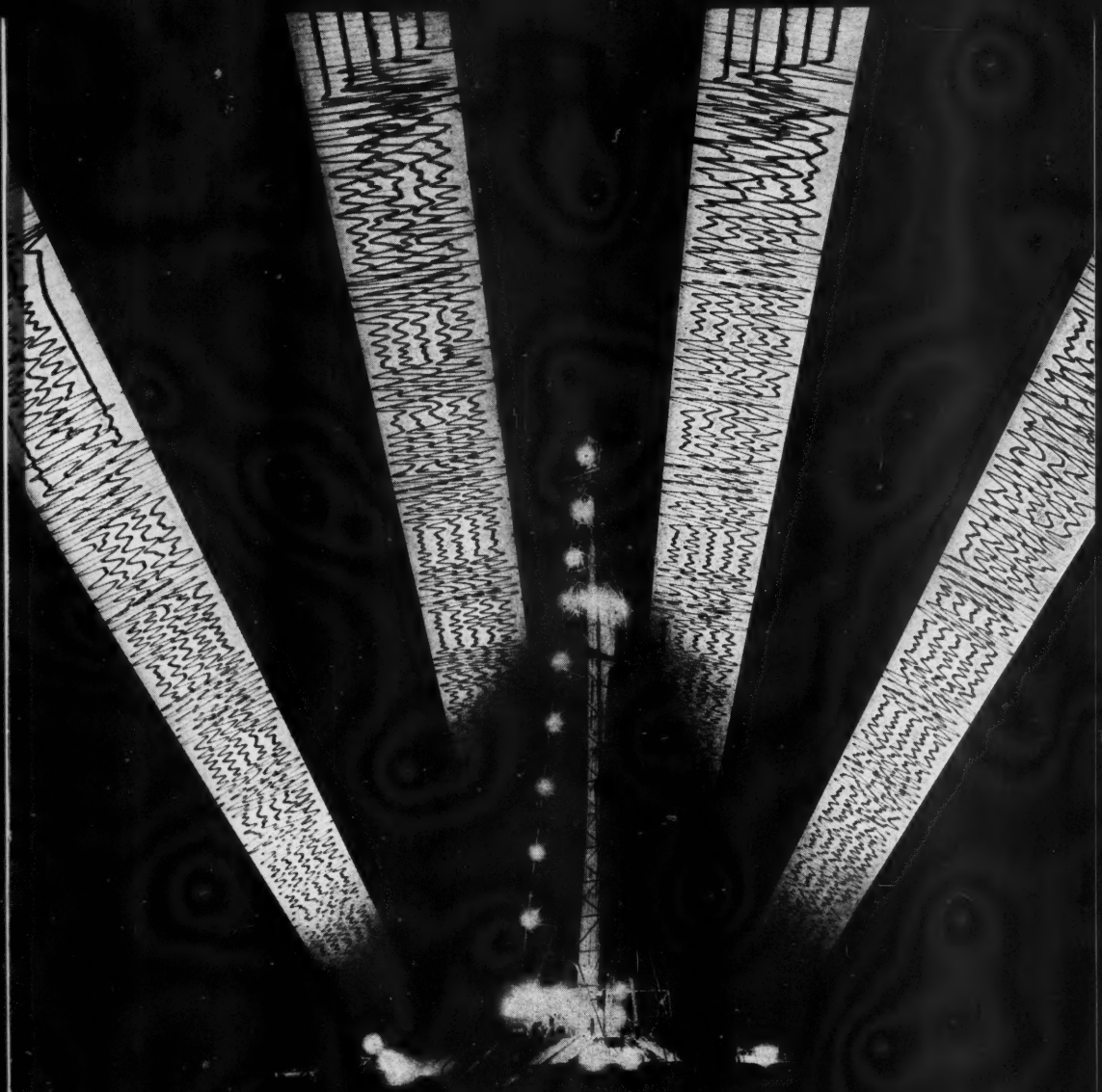

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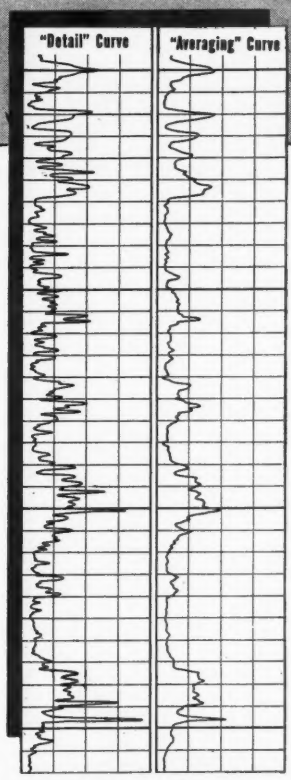

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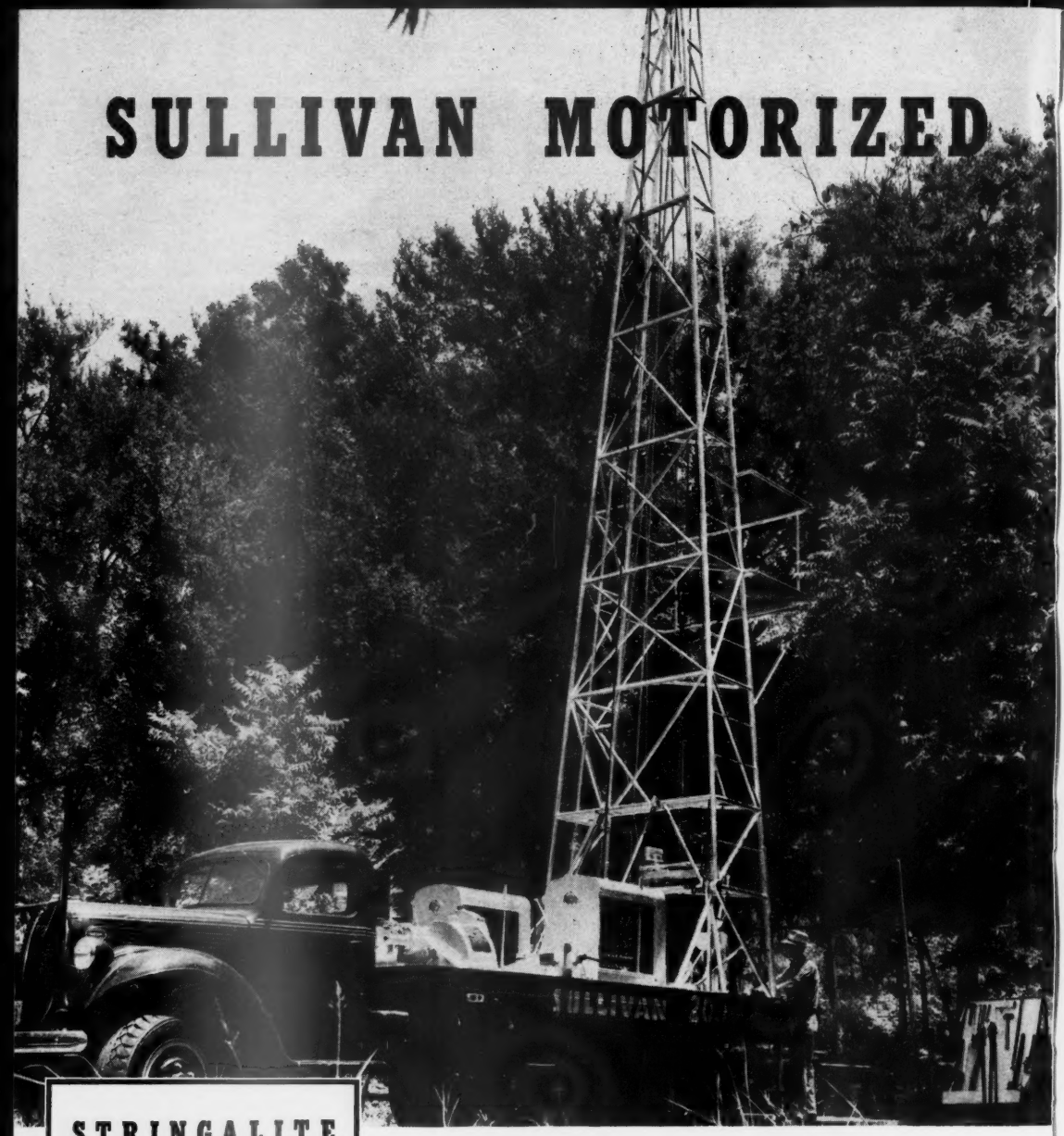

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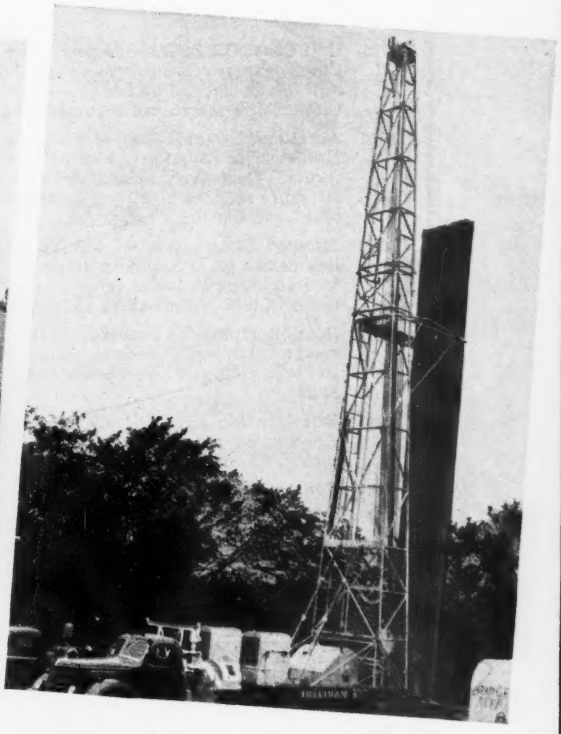

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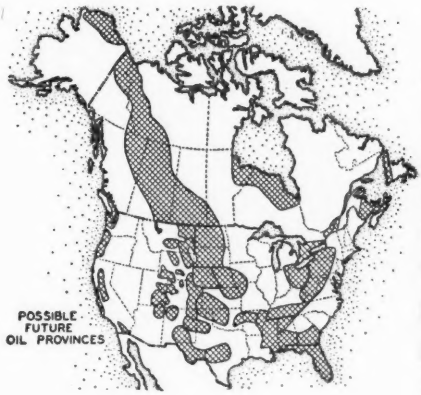

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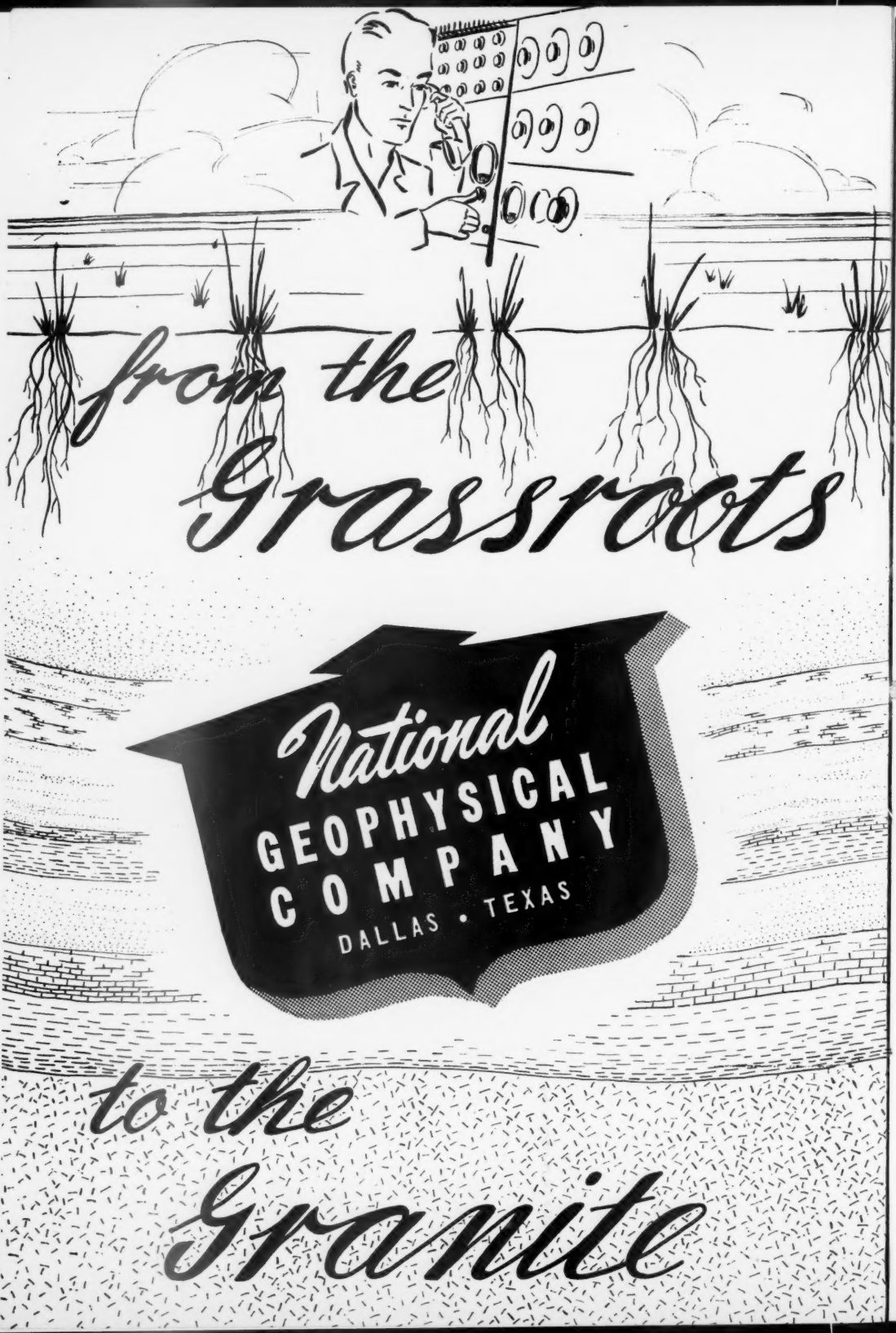
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Granite

Complete Coring Service with REED CORE DRILLS

The REED Kor-King CONVENTIONAL

The REED 'BR' Wire Line

DEPENDABLE

SUB-SURFACE DATA in your WILDCATTING OPERATIONS

. . . with either the REED "BR" Wire Line Drilling-Coring outfit or with the REED "Kor-King" Conventional type Core Drill.

For further information on these Core Drills
SEND FOR BULLETINS C-415 AND K-1141

REED ROTARY DRILLING TOOLS
SPEED-ECONOMY-DURABILITY

REED ROLLER BIT COMPANY
P. O. BOX 2119 HOUSTON, TEXAS

Here's why we use
HUGHES
Type 'J' CORE BITS

- Large diameter core recovered.
- Double Core Catcher---same assembly is used for both hard and soft formation coring.
- Hard and Soft Formation Cutter Heads fit the same box connection in lower end of Working Barrel --- easily interchanged for varying formations.
- Floating Core Barrel.
- Replaceable Core Barrel Tip.
- Vent for relieving pressure above core as it enters core barrel.
- Plug for keeping Core Barrel clean when running in hole.
- Ease of dressing and handling.
- Simplicity and long life of parts.
- Rugged strength of all parts for safety.

HUGHES TOOL COMPANY • HOUSTON TEXAS